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SURVEY OF ADVANCED PROPULSION SYSTEMS FOR SURFACE VEHICLES

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Future military needs in propulsion systems for surface vehicles are examined in order to provide guidance for Technology Base programs directed at improved engines, transmissions, thrusters and fuels. It is observed that there is a physical tendency for power-generating systems to grow heavier per horsepower as output increases. This trend runs counter to the requirements of more mobile vehicles which need more power for less weight. These

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effects are quantified and it is shown that the performance demands of many projected military surface vehicles severely restrict the propulsion system options that technology can provide.

The relevant Technology Coordinating Papers (i.e., the Army Land Mobility TCP and the Navy Ocean Vehicles TCP) are used to review existing Technology Base programs. The findings of this study are reached by comparing the goals of existing programs with the apparent propulsion system options derived from projected vehicle performance requirements. A general conclusion is that, because of the severe impact on propulsion system characteristics of demands for high mobility, both Services could greatly improve Technology Base program guidance by more careful definition of future needs.

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ABSTRACT

Future military needs in propulsion systems for surface vehicles are examined in order to provide guidance for Technology Base programs directed at improved engines, transmissions, thrusters and fuels. It is observed that there is a physical tendency for power-generating systems to grow heavier per horsepower as output increases. This trend runs counter to the requirements of more mobile vehicles which need more power for less weight. These effects are quantified and it is shown that the performance demands of many projected military surface vehicles severely restrict the propulsion system options that technology can provide.

The relevant Technology Coordinating Papers (i.e., the Army Land Mobility TCP and the Navy Ocean Vehicles TCP) are used to review existing Technology Base programs. The findings of this study are reached by comparing the goals of existing programs with the apparent propulsion system options derived from projected vehicle performance requirements. A general conclusion is that, because of the severe impact on propulsion system characteristics of demands for high mobility, both Services could greatly improve Technology Base program guidance by more careful definition of future needs.

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CONTENTS

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SUMMARY AND FINDINGS

This report is presented in the following three levels of detail:

- A brief review is provided in this summary section, with little detail, but covering the main observations.
- The data and rationale on which the observations are based are given in the main body of the report.
- The detailed supporting analyses that underlie the rationale are presented in a series of Appendices. The Appendices are intended to give full details so that the reader may scrutinize the validity of the results.

SCOPE AND ORGANIZATION (Summary of Section 1)

The basic purpose is to conduct a survey of advanced propulsion systems for new types of military surface vehicles. The results of the survey are to be used for inputs to the Technology Coordinating Papers (TCPs) on surface vehicle technology. The survey is intended to define the state of the art, point out attractive opportunities, and indicate gaps in the current programs.

The scope may be established by definition of the terms used in the above paragraph.

- "Propulsion systems" include four elements--energy storage (fuels), energy conversion (engines), energy transfer (transmissions), and energy delivery (thrusters).
- "Advanced" implies the work funded in the 6.1, 6.2, and 6.3A program areas.
- "Surface vehicles" means all military land vehicles, ships, and submarines.

* The TCPs referred to are the Army Land Mobility TCP and the Navy Ocean Vehicle TCP.

The approach taken is unusual in that it avoids mission analyses but uses instead projected military vehicle requirements in mobility, range, and size as a means of defining future propulsion requirements. Military needs are reviewed in Section 2, the state of the art in Sections 3 and 4, and resulting gaps and opportunities in Section 5.

MILITARY NEEDS (Summary of Section 2)

It is shown in the report that Technology Base activities in propulsion systems are required primarily to satisfy the needs of combat and close-support vehicles. Other military vehicles can rely on established technology and on commercial advances or the foreseeable future.

In both Services, the trend in combat vehicle development is toward greater mobility without sacrificing range. An analysis is made of what this trend means to propulsion technology with these observations:

* Demands for greater mobility are being met with vehicles with greater specific power (hp/ton).
* Increasing specific power will tend to shorten range--how severely depends on the increase in specific resistance.
* For weight-limited vehicles, higher mobility demands reduced specific weight limits on the propulsion system.
* For volume-limited vehicles, higher mobility demands reduced specific volume limits on the propulsion system.
* For many high-mobility vehicles, providing adequate range is a severe problem which places demands on specific fuel consumption improvements.
* There are physical and cost limits that place upper bounds on the size of many vehicles.

Quantitative levels of specific weight, specific volume, and total power of propulsion systems are established for various military needs. These are used in the next section to sort out which propulsion system components are potentially useful for military surface vehicles.

TECHNOLOGY POTENTIAL (Summary of Section 3)

It is pointed out at the beginning of this section that contrary to the common "economy of size" assumption, propulsion systems <u>increase</u> in specific weight and volume as size increases in the power ranges of military interest. Higher mobility, by demanding lower specific weights and volumes, thus tends to restrict propulsion options as power increases. By sorting through the quantitative values that bound current and foreseeable technology and comparing these values with the limits established in Section 2, the following observations are made:

<u>On Engines</u>

- External combustion engines (nonnuclear) are not suitable for high-performance land vehicles or for high-speed (>50 knots) sea vehicles.
- For high-performance land vehicles, the options are diesel or gas-turbine engines. Spark ignition or rotary engines could qualify for land vehicles on a weight and volume basis, but are not developed in the sizes needed.
- For ocean-going high-speed vehicles, the only current option is the gas turbine.
- For coastal high-speed sea vehicles, the gas turbine is the preferred choice by weight and volume, though other internal combustion engines can be used.
- For long-range sea vehicles, nuclear propulsion offers great advantages. At current weight and volume limits, however, it can only be used for fleet submarines and for Navy combat ships over 15,000 tons without degrading performance.

On Transmissions

- Current mechanical/hydraulic transmission technology can meet weight and volume requirements for both land and sea high-performance vehicles. At the power levels required for sea vehicles, however, the technology has not been reduced to practice.
- Electric power transmission can offer advantages in land vehicles where multipoint power distribution is needed. Both cost and reliability have been obstacles. but new technology is in sight which could remove those blocks.
- Where large amounts of power must be distributed in difficult geometrical situations in sea vehicles, superconducting electric power transmission is attractive. For high-performance vehicles, specific weight limits may favor the ac over the dc approach.

On Thrusters

- The track is the preferred high-mobility land vehicle thruster for severe terrain and is unlikely to be displaced.
- The wheel has considerably less tractive ability than the track, but is much lighter. All-wheel drive and articulation can improve the traction of a wheeled vehicle to where it can compete with the track in high-mobility applications, except for heavy payloads in severe terrain.
- For high-speed ships, the best thruster options are the supercavitating propellor or the waterjet

On Fuels

- The recently changed petroleum supply situation requires a change from the trend to develop specialty fuels to the development of more universally useful petroleum fuels and possible alternative fuels.
- Petroleum fuels are uniquely suited to the needs of high-performance vehicles and are the only choice among chemical fuels for volume-limited vehicles where range is important.

- Major further reductions in specific fuel consumption for engines of interest are not to be expected.
- For weight-limited vehicles, liquid hydrogen is a possible alternative fuel. If the vehicle is also range-limited, liquid hydrogen can give improved performance.
- For any long-range, high-performance vehicle, the ultimate solution to fuel problems is nuclear propulsion. Developed nuclear systems are heavy but can be used in large ships and submarines where high specific weights are acceptable. Lightweight nuclear power is conceptually feasible (see Appendix G), but has not been developed to acceptable safety, reliability, and maintainability standards for military use.

TECHNOLOGY BASE PROGRAMS (Summary of Section 4)

Land Vehicles

Technology Base programs for propulsion of land vehicles are described in three documents

- The Land Mobility TCP
- The TACOM 20-year Propulsion Systems Plan
- The AMC Long-Range Fuels Program.

The Land Mobility TCP establishes a set of priority programs which center on the establishment of a mobility evaluation methodology and exploratory development of high-mobility vehicles. The level of funding indicated for propulsion system Technology Base programs for FY 74 is approximately

Power plants	\$3.0 Million
Transmissions and line of drive	\$0.5 Million
Suspensions and running gear	\$2.1 Million
Fuels, lubricants, and chemicals	\$1.8 Million
Controls and diagnostics	\$0.5 Million

The TACOM 20-year Propulsion Systems Plan for Combat Vehicles is based on developing propulsion system components in advance of definitive vehicle needs. The elements of the program include

- Advanced diesel technology
- Advanced turbine technology
- 1000-hp stratified charge engine
- Rankine and Stirling engine technology
- Electric-powered vehicles
- Advanced transmission technology
- Improved air filters and heat exchangers
- Systems integration technology

This program appears to be more diverse than is needed to meet foreseeable needs or to fit within the projected budget.

The AMC Long-Range Fuels Program provides guidance for Army power plant R&D and establishes a fuels R&D program. The guidance for power plant R&D is basically to emphasize multifuel use capabilities on all combat-zone engines immediately. For the longer term, ability to use hydrogen should be developed. The Fuels R&D Program itself is revised to transfer emphasis from quality control to availability.

Sea Vehicles

Technology Base programs for propulsion of sea vehicles are included in two documents

- The Ocean Vehicles TCP
- The Nonnuclear Propulsion Systems R&D Program

In addition, observations are made on the nuclear propulsion program but are not based on any document.

The Ocean Vehicles TCP shows a major emphasis on high-speed oceangoing ships with the immediate priority a 2000-ton SES. The funding that is shown includes all the 6.3 program area and hence includes both Technology Base and Technology Application programs. Over the six-year period covered (FY 73-FY 78), the total funding breaks down as follows:

Conventional ships	$ 93 Million
Crafts and boats	$ 39 Million
Hydrofoil ships	$138 Million
Surface effects ships	$448 Million
Air-cushion vehicles	$ 95 Million
Multihull ships	$ 46 Million
Submarines	$ 80 Million
Submersibles	$ 48 Million
Towed and tethered vehicles	$ 17 Million

The development of unconventional, high-speed, oceangoing ships appears to be a high-risk venture in terms of propulsion system requirements.

The Nonnuclear Propulsion Systems R&D Program for Navy Ships proposes a program to develop propulsion system components independent of 6.4 area vehicle demands. The proposition is the same as the TACOM 20-year Engine Plan, i.e., to predevelop propulsion system components in advance of definitive vehicle needs. The program includes:

- Development of a family of gas turbine propulsion systems
- Automatic steam plant controls
- Lower weight transmissions
- Improvement of waterjet propulsors
- Design criteria for high-speed propellors
- Automatic propulsion control and diagnostic systems
- A ship for test and engineering of propulsion systems

This program includes both Technology Base and Technology Applications areas. In terms of "predeveloping" propulsion system hardware, only the gas-turbine marinization and the superconducting transmission programs were funded prior to FY 75.

The Nuclear Propulsion R&D Programs have been directed at increased core life and improved reliability and maintainability. Techniques for reducing size and weight exist, but run counter to the stated goals and have not been pursued.

ISSUES AND FINDINGS (Summary of Section 5)

Land and sea vehicles can be treated separately since there is virtually no overlap in their demands on propulsion systems. There are two reasons

- The vast difference in size between land and sea vehicles
- The much greater endurance demanded of sea vehicles

Land Vehicles

Issue: Dependence on Commercial Technology

Finding: The push toward higher power is separating the Army from its traditional commercially supported Technology Base. Increasing emphasis and expenditures in DOD Technology Base activities will be needed to support this move. Current levels of funding (Section 4) seem inadequate when compared to aircraft propulsion R&D expenditures.

Issue: Engine Types

Finding: There is a critical need to define future land vehicle requirements in installed power more closely in order to formulate a rational Technology Base engine program. A major deficiency in the current program is that the already meager resources are split between supporting high-powered diesels and equivalently powered gas turbines. A decision to go one way or the other would help alleviate this problem. A corollary finding is that in the 200- to 2000-hp range Technology Base activities related to engines other than diesels or turbines are not needed.

Issue: Conventional vs. Electric Transmissions

Finding: In FY 75 the Army has dropped all electric transmission projects after a steadily decreasing yearly allocation for many years. There is a need to continue some Technology Base activity in this area, at least to monitor the rapidly changing technology in solid-state devices (see Section 3) and as long as articulated, wheeled vehicles are of possible interest.

Issue: Wheel vs. Track as High-Mobility Thrusters

Finding: The wheel and the track will continue to be the preferred thrusters for Army vehicles. However, there is an urgent need for more careful and exact terrain operating specifications for off-road vehicles since it is these specifications and not vehicle design details which determine whether the track or wheel is to be used. As the specified terrain conditions become more severe the track becomes mandatory (see Appendix E). On the other hand, the articulated wheeled vehicle can provide greater agility and speed under less severe conditions. Correct specifications are thus of critical importance.

Issue: Definition of Mobility Limits

Finding: Mobility modelling and analysis are not providing adequate data on mobility limits, and such data are needed to guide Technology Base activities. A combined experimental-analysis program with the following goals is apparently needed:

- Determine if agility rather than speed is the power-determining factor (as suggested in Appendix E).
- Find what levels of agility/speed give attractive pay-offs in reduced vulnerability (i.e., quantify the type of study done in the HELAST project).
- Determine agility/speed effects on offensive capabilities and needs.
- Assess, for practical scenarios, what terrain limitations there are on the use of power (extension of Appendix E).

This program would require building and testing purely experimental vehicles in order to extend and validate the mobility and design models. The results could then be used to establish specific power and thruster specifications for evaluating conceptual vehicle designs and for guidance of Technology Base programs.

Issue: The Family Concept for Components

Finding: There is need to study the conditions under which the family concept in engines, transmissions, and running gear would be useful. Certainly it would seem necessary to have the results of the mobility study suggested above before reasonable family ranges could be determined. Other factors would be the projected total demand for each family member and an assessment of the risk of obsolescence through application of new technology at a later date.

Sea Vehicles

Issue: Emphasis on High-Speed Ships

Finding: The demand for high-speed oceangoing ships could not be met until recently because propulsion systems were too heavy (Section 3, and Appendix F). The marinized second-generation aircraft gas turbines (e.g., the LM 2500) has changed this picture in recent years. Since then, virtually all nonnuclear Technology Base activities in propulsion systems for sea vehicles have become directed at high-speed ships (Section 4).

Issue: Development of a Family of Marinized Gas Turbine Engines

Finding: In view of the low demand situation for marine gas turbines, a careful study should be made of the cost-effectiveness of predeveloping a family of engines. A corollary finding is that there is no perceived need for gas turbines over 40,000 hp (see Section 2, Size Limits).

Issue: Nuclear Propulsion as a Solution to the Range Problem

Finding: A reduction in weight by a factor of two would make nuclear propulsion clearly superior to gas turbines for escorts of DD 963 type. A reduction of weight by a factor of 8 to 10 would make nuclear propulsion feasible for high-speed ships of the SES 2000 type. Such weight reductions are technically feasible and undoubtedly will appear in time in commercial use

(Appendix G). A directed Technology Base program could reduce the time to reach lightweight nuclear propulsion systems by a big factor.

Issue: High-power Lightweight Transmission Systems

Finding: In general, lightweight transmission systems for high-speed ships require higher rotational speeds, more gearing, and different types of gears than have been used traditionally in the Navy. This technology is available at 4000 hp in helicopters and has been extended to 25,000 hp in design studies (for example, in the SES 2000 designs). Technology Base attention should be directed to applying this technology at the power levels required for Navy applications (up to 40,000 hp).

In pursuing the development of superconducting transmissions, the trade-off between ac and dc systems at the high-power levels required should be examined more carefully. It is possible dc systems may become too heavy as power level is scaled up.

Issue: High-Speed Thrusters

Finding: High-speed ships need supercavitating propellers or waterjet thrusters. Both these devices are receiving adequate attention in Technology Base activities (Section 4). The relatively low efficiency of waterjets (~50 percent) is important because gas-turbine-powered, high-speed ships are range-limited (Section 2, and Appendix C). In the future, lightweight nuclear power could make this deficiency less important.

Issue: Military Usefulness of Petroleum-Fueled High-Speed Escorts

Finding: High-speed petroleum-fueled escorts will require frequent refueling. The effect of this limitation on possible missions should be evaluated, but it appears likely that ocean-going high-speed ships will not become practical Navy vessels until lightweight nuclear power is available in the indefinite future, or until hydrogen is accepted as an operational fuel. If so, then major changes in Technology Base emphasis are in order.

1. SCOPE AND ORGANIZATION OF SURVEY

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1. SCOPE AND ORGANIZATION OF SURVEY

1.1 Purpose

This study was conducted at the request of DDR&E, Research and Advanced Technology Division, under Task Order 102 (Appendix A). Mr. Robert Zeim was the DDR&E point of contact and has provided a great deal of help and counsel in assembling the information presented in this report.

Technology Coordinating Papers (TCPs) are relatively new; those on Surface Vehicle Technology with which this study is concerned are the first produced in this area of technology. It was recognized initially that each TCP would have to be updated and revised at intervals to be useful on a continuing basis. The intent of the Task Order was to provide an independent survey of the area of technology which could provide additional inputs to the TCPs as they came up for review and revision.

The purpose was stated definitively in the Task Order as follows:

> "... to conduct a survey of advanced propulsion systems for new types of land vehicles, ships and submarines. This survey will be used to provide inputs to the TCPs on surface vehicle technology and on topics relating to advanced propulsion and power systems. It will define the current state of the art, point out attractive opportunities and indicate gaps in the existing program. A study of the feasibility and military utility of light weight, wheeled air cushion vehicles will be completed. Propulsion and power systems analysis for small submarines will be completed."

This report concerns itself with the general survey that is requested. The specific studies on lightweight air-cushioned vehicles (ACV) and small submarines are the subject of separate reports that are in preparation.

1.2 Scope

The overall scope of the survey can be outlined by defining the specific meaning of the terms used above in stating the purpose.

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- What is meant by "propulsion systems"? A propulsion system is taken to consist of four basic components--fuel, engine, transmission, and thruster. It is the complete system that provides the vehicle with the ability to move. It is not taken to include maneuvering control systems such as steering devices, but it does include control systems for the propulsion system itself. Since propulsion control systems do not contribute significantly to weight and volume requirements, they are not included as a separate basic component.
- What is the significance of "advanced"? This refers to Technology Base R&D work which seeks to make advances in technology but is not directed to a specific vehicle that is in engineering development. The RDT&E program area (Program 6) can be conveniently divided into two types of activities--those which are directed at answering a specified military need with new equipment (Technology Applications) and those which are directed at improving technology for some later application (Technology Base). Technology Base activities are funded under program areas 6.1 Research, 6.2 Exploratory Development and partly in 6.3 Advanced Development while Technology Applications fall under 6.6 Operational Systems Development, 6.4 Engineering Development and partly in 6.3 Advanced Development. Because of the overlap in the 6.3 area, it has become common to designate it in two parts, 6.3A for Technology Base projects and 6.3B for Technology Applications projects. It is sometimes difficult, without detailed investigation, to determine on which side of the line 6.3 projects belong. Where any such ambiguity is recognized in this study, it will be pointed out.
- What is the purpose of the TCPs? The specific TCPs referred to in the Task Order are:
  "Land Mobility Technology Coordinating Paper," 1 November 1973, prepared by the Army.

"Technology Coordinating Paper--Ocean Vehicles," 1 June 1973, prepared by the Navy.

The Air Force did not participate in either of these TCPs because of its minor interest in surface vehicles.

The objectives of a TCP are set forth in a DDR&E memorandum, "Background and General Guidance on TCPs" (Ref. 1), which states that "The TCP is intended to define:

- Areas of scientific endeavor and specific engineering advances needed to meet future military requirements and to solve current problems.
- The programs underway or planned by each Service to fill these needs.
- The important gaps in the technology, if any, which exist at presently projected funding levels.
- The ways in which the technology area can be strengthened--these are in the form of recommendations from the 'field' for consideration by management."

Major purposes of the TCP are thus to relate R&D programs to military needs, to expose any gaps, and to recommend ways to strengthen the programs.

To accomplish these purposes, a format is established in the same memorandum. The information in TCPs is to include:

1. Current program
2. Military requirements for new technology
3. Current priorities
4. Cost of current program
5. Significant unfunded areas
6. Recommendations for program improvements
7. General observations

- <u>What types of propulsion systems are to be considered?</u> The survey will cover any type of advanced propulsion system suitable for current or future military surface vehicles.

Specifically, in addition to conventional land and sea vehicles, it will include the propulsion requirements of such advanced concepts as hydrofoil ships, surface-effects ships, air-cushion vehicles, high-mobility articulated land vehicles, etc. Throughout this report the term "surface vehicles" will be used to include all these vehicles of interest.

1.3 Approach

The basis of the approach taken in this survey is unusual in that it avoids mission analyses but uses instead general military vehicle requirements in mobility, range, payload (size), and cost as the means of defining future propulsion requirements. Such an approach is satisfactory for Technology Base guidance though it would not serve for Technology Applications work.

The steps taken in following this approach with references to the appropriate subsections of this report are as follows:

1. Reduce the broad field of coverage defined above to manageable size by sorting out which areas can rely on established technology and which will need improved technology (Section 2.1).
2. Reduce military vehicle requirements in mobility (Section 2.2), range (Section 2.3), and size (Section 2.4), to equivalent propulsion system specifications in total power, weight, and volume (Section 2.5).
3. Examine the potential of various propulsion system components to meet the specifications established in Section 2.

   Combustion Engines (Section 3.2)
   Nuclear Engines (Section 3.3)
   Transmissions (Section 3.4)
   Thrusters (Section 3.5)
   Fuels (Section 3.6)

4. Survey current and planned military Technology Base programs in propulsion systems.

Land Vehicles (Section 4.1)
Sea Vehicles (Section 4.2)

5. Relate the specifications (Section 2), the potential (Section 3), and the programs (Section 4), to define gaps and opportunities and to examine military alternatives in propulsion systems.

   Land Vehicles (Section 5.1)
   Sea Vehicles (Section 5.2)

2. MILITARY NEEDS

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2. MILITARY NEEDS

2.1 Vehicles Requiring Advanced Propulsion Systems

From the point of view of the demands placed on the propulsion system, it is convenient to consider three classes of military vehicles:

- High-Performance Vehicles - includes all combat and close support vehicles where the prime need is for performance in terms of speed and range under all kinds of terrain conditions.
- Transport Vehicles - includes all noncombatant transports where the prime need is efficient cargo-carrying capability.
- Special-Purpose Vehicles - includes all combatant and non-combatant vehicles where the prime need is some special function which overrides both high-performance and transport efficiency considerations.

This classification permits a sorting out of military propulsion system needs which greatly simplifies the task of this report. In the following paragraphs this sorting process is undertaken and the results are summarized in Table 2-1.

High-performance vehicles, as a class, place the greatest demands on propulsion systems. There is a constant demand for improved performance in combat vehicles and the prime limitation in meeting this demand is the capability of the propulsion systems. The best known military vehicles are in this class, e.g., tanks, aircraft carriers, destroyers, armored personnel carriers, etc. Because these are strictly military vehicles, and because they are pushing the state of the art in vehicle design, the propulsion systems for them must be provided from DOD research and development work.

In transport vehicles, military needs are the same as commercial needs. The goal of each is to move given payloads in a time-and-cost-effective manner over given distances. Commercial transport capabilities in surface vehicles have advanced significantly in recent years. As a result, both the Army and the Navy are, as a matter of policy, relying more and more on commercially developed vehicles to satisfy their transport needs. The Army some years ago adopted the policy of using commercial truck engines, and more recently, as a result of the Wheels study (Ref. 2), has begun using complete commercial vehicles. The Navy is similarly expecting to use commercial cargo ships to rebuild its aging transport fleet. Furthermore, the Navy is relying on the Maritime Administration to develop the technology needed to improve ocean transport (Ref. 3).

TABLE 2-1. CLASSES OF MILITARY VEHICLES AS DEFINED FOR THIS STUDY

Class	Prime Specification	Military Development	Commercial Sources
High-Performance	High speed/range in adverse terrain conditions (i.e., rough seas, off-road)	Land: Tanks, Armored Carriers, High mobility support trucks Sea: Carriers, Escorts, Submarines, Coastal Patrol Vessels	(No equivalent)
Transport	Optimize payload-carrying ability with respect to time/cost	(Can use commercial sources)	Land: Medium- and low-mobility trucks Sea: Cargo ships, Tankers
Special-Purpose	Optimize compatibility with a special payload	Land: Bridging Vehicles, Mine Clearing Vehicles, Air-transportable Construction Vehicles Sea: Beach Landing Vehicles, Underway Resupply Vehicles, Deep-Submergence Vehicles	Land: Construction equipment Sea: Tugs, Floating Cranes, Drydocks

The situation with regard to special-purpose vehicles is mixed. Some types can be directly supplied from commercial sources and some need development. For example, bulldozers, graders, cranes, etc. for construction work; and tugs, floating cranes, drydocks, etc. for ship handling and repair can all be commercial equipment; on the other hand, each Service has special needs which have no equivalence in civilian life. The Army requires special combat-support vehicles for such purposes as bridging, mine clearing, close-support construction, etc. Similarly, the Navy needs the ability to resupply combat ships at sea, vehicles for landing supplies at unprepared beaches, search and rescue deep-submergence vehicles, etc. It is characteristic of special-purpose vehicles that their design is optimized around one particular function. Many are not required in great numbers, and for this reason would not warrant development of a special advanced propulsion system. Even if that is not the case, the complications associated with such vehicles stem from the fact that they must perform specialized tasks; hence, the usual design decision is to use a proven propulsion system to satisfy both cost and reliability requirements.

The conclusion to be drawn from this discussion is that propulsion system characteristics are the pacing item from the military viewpoint only in the development of high-performance vehicles. We should expect that military Technology Base activities in propulsion systems would therefore be largely directed at improving military combat and close combat-support capabilities, and that is where the bulk of our attention in this report will be directed. The needs for transport and special-purpose vehicles will not be discussed in a general way but only as they apply in a few special cases.

2.2 Mobility

Both Army and Navy have adopted mobility as a prime requirement of all advanced combat vehicle developments. Intuitively, it is clear that warfare has been moving to greater and greater mobility in modern times. The "armored fortress" concept of the battleship has been discarded for some time, and there are indications that the heavily armed, heavily armored tank may become obsolete (Ref. 4). It is not the intent of this survey to argue the merits of the decision to seek mobility. What will be done here is to determine the implications of increased mobility on future propulsion systems needs.

To interpret the mobility requirement it must be defined more closely. In the Army program to develop an analytical methodology for assessing vehicle mobility (Ref. 5), "Mobility" is defined as "a measure of the vehicle's capability to maneuver, reflecting both the vehicle's ability to negotiate difficult terrain and the speed it can sustain over negotiable terrain." There is a natural division in this definition:

1. Agility--i.e., the ability to maneuver in the immediate local terrain which requires turning capability, quick acceleration/deceleration, and the ability to negotiate obstacles. In combat vehicles, agility is of major concern to the vehicle commander in achieving combat effectiveness.
2. Transport speed--i.e., the ability to sustain speed over specified terrain. Transport speed is of major concern to the battle commander in deploying his forces effectively.

Most important, mobility must be maximized in off-the-road situations on land and in rough seas on the ocean. A "Super-Highway Army" and a "Fair-Weather Navy" have limited usefulness. The limiting design condition for combat mobility of ocean vehicles is generally to maximize the top speed under adverse specified "resistance" conditions (i.e., rough seas). In land vehicles, the limiting design condition is usually to meet combined speed and slope-climbing specifications. In Appendices C, D, and E, these design limits are considered in detail and it is shown that a basic measure of mobility is motive power per unit weight or specific power (generally expressed in units of hp/ton).

Considerable variation in mobility can be caused by the different thrust devices that may be used to turn the available power into a driving force. For example, the differences between tracked and wheeled land vehicles, or between propeller-driven and waterjet-propelled ships are obvious. Nevertheless, in a given situation, the vehicle with the greater specific power has the greater potential mobility. Mobility increases as power is increased until a point is reached where thruster efficiency drops so rapidly that additional power cannot be utilized effectively.

A feeling for the relationship between specific power and mobility can be obtained by looking at the range of familiar vehicles shown in Table 2-2.

TABLE 2-2. SPECIFIC POWER OF COMMON VEHICLES

Vehicle	Approximate Specific Power in hp/ton
LAND	
Freight Train	1
Long Distance Truck	10
Family Car	75
Sports Car	150
Racing Car	300
SEA	
Large Tanker	0.1
Freighter	1
Fishing Boat	10
Speed Boat	80
Racing Boat	200
AIR	
Light Airplane	80
Commercial Jet Aircraft	300
Helicopter	400
Fighter Aircraft	1,000

The specific power of the military vehicles of interest here are shown in Figs. 2.1 and 2.2. The data have come from a number of sources and are tabulated in Appendix B. Figure 2.1 shows installed power per unit weight for Army vehicles and is simply illustrative of the levels of specific power that high-performance Army vehicles are using and are projected to use. In actuality the delivered thrust power is a jagged curve varying with velocity, slope (or acceleration) and

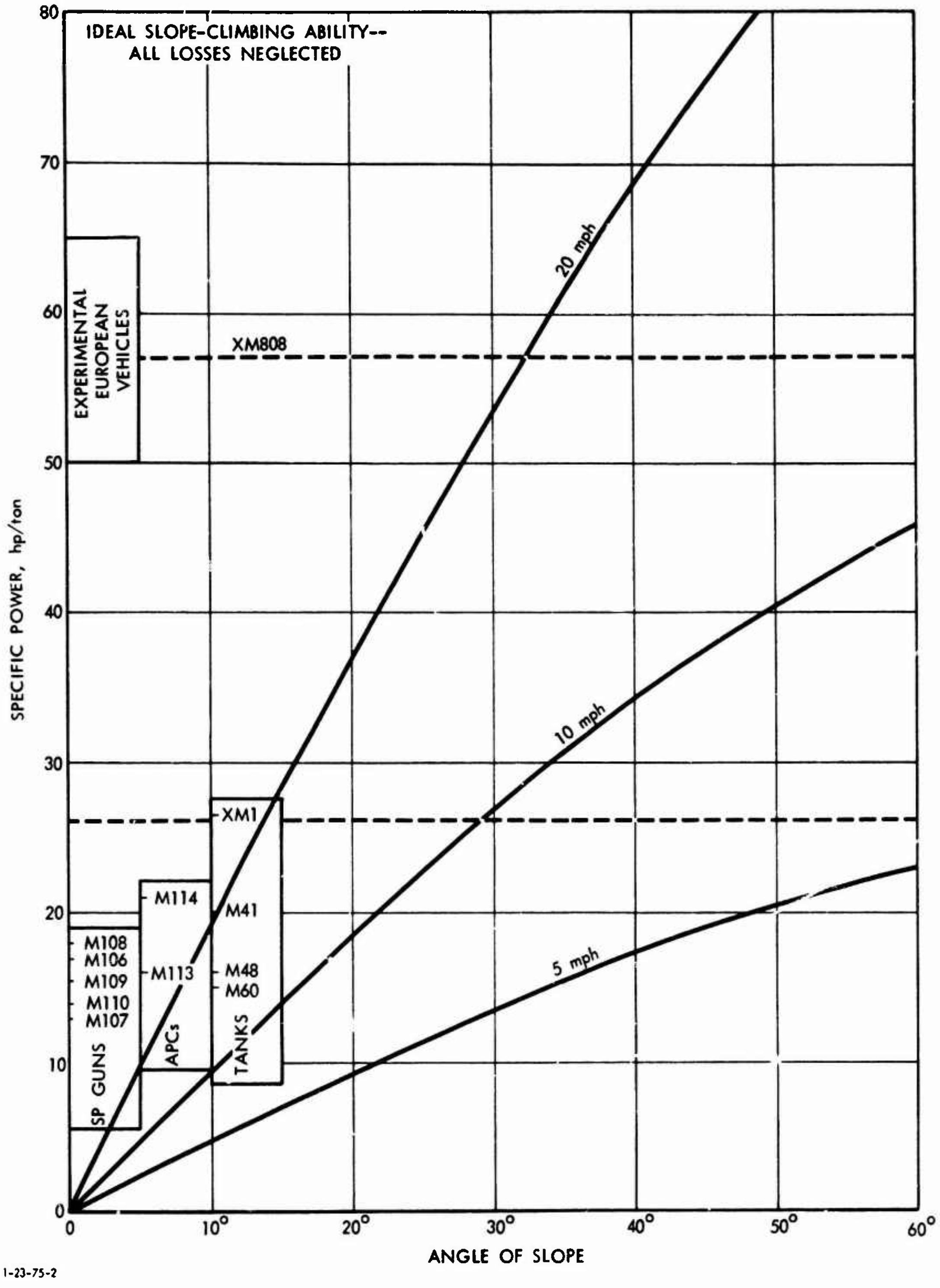

FIGURE 2.1. Specific Power for Army Vehicles

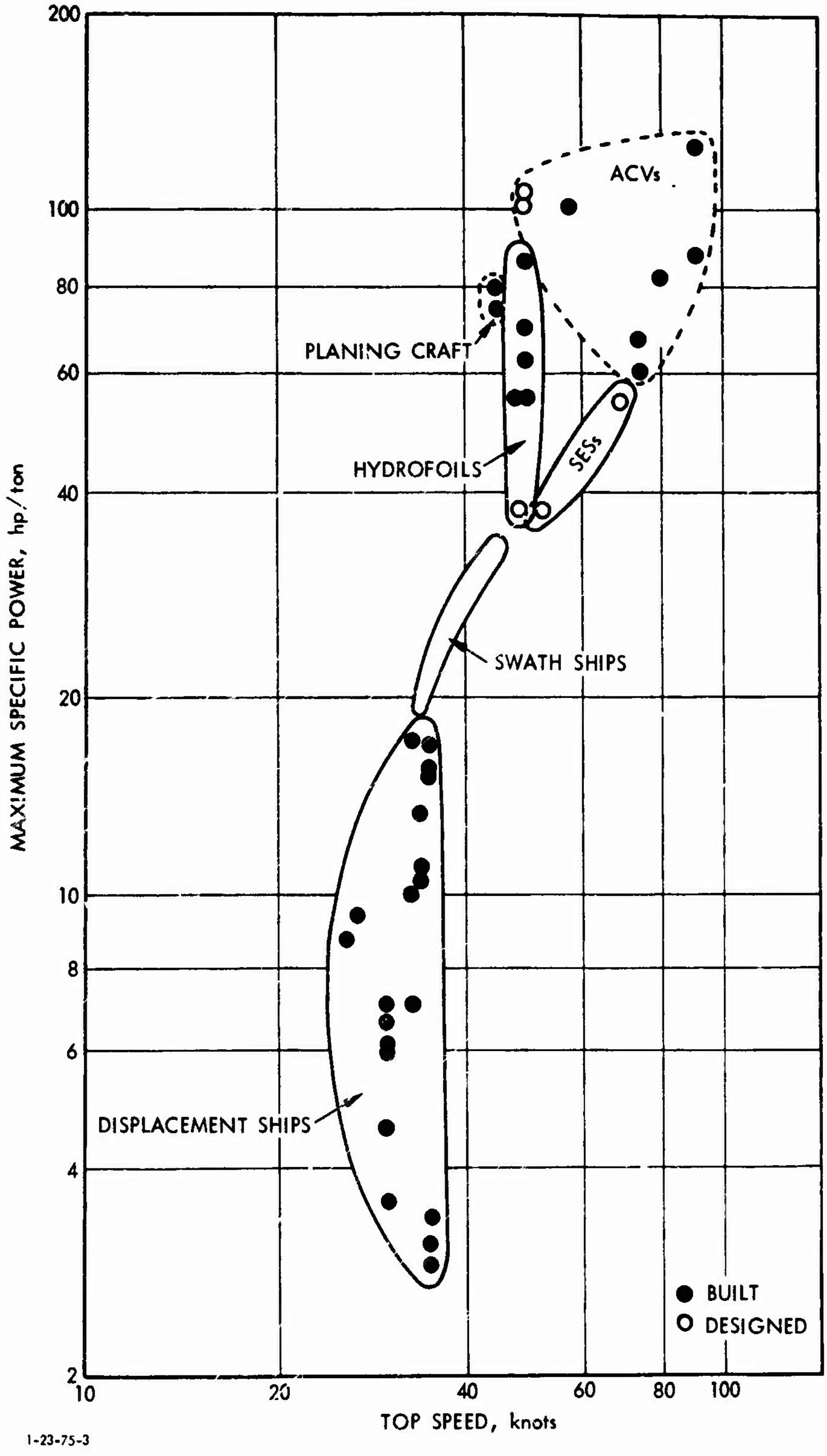

FIGURE 2.2. Specific Power for Navy Ships

ground conditions (see Appendix E). The peak of this curve, together with the combined transmission-thruster efficiency (η_{xt}), will determine the required level of installed power. Without this detail relative performance can be judged from Fig. 2.1. For example, the XM-1 will climb a given slope at a little less than twice the speed of the M-60.

Similarly, Fig. 2.2 shows installed power per unit weight* for Navy ships. The trend to higher specific powers is even more evident here than for land vehicles. The reason is obvious--on land power is nearly proportional to velocity while at sea power varies at least as velocity cubed.

The level of specific power establishes one limit on the propulsion system in the following way. Overall design considerations constrain what percentage of the total vehicle weight can be assigned to the propulsion system (see Appendix C). Once this percentage is established, the specific power of the vehicle and the specific weight of the propulsion system are inversely proportional, as shown in Fig. 2.3. The observation to be made from this plot is that military demands for higher hp/ton place quite restrictive demands on the specific weight of the propulsion system. This limits the options in engines, transmissions, and thrusters that can be used, as will be discussed fully in Section 3.

Higher hp/ton also limits the amount of fuel that can be carried, which means the endurance of the vehicle is reduced as specific power increases. A simple quantitative relationship can be derived as follows. If we assume that the drag of the vehicle does not change as it uses fuel, then the endurance is simply the weight of fuel divided by the rate at which fuel is consumed.

$$E = \frac{W_f}{P_e(sfc)} = \frac{W_f}{W_v}\,\frac{W_v}{P_e(sfc)} \quad , \tag{2.1}$$

*Where not otherwise indicated, short tons are used for land vehicles and long tons for sea vehicles in this report.

where

E = endurance

W_f = weight of fuel

W_v = gross weight of vehicle

P_e = power from engine

sfc = specific fuel consumption

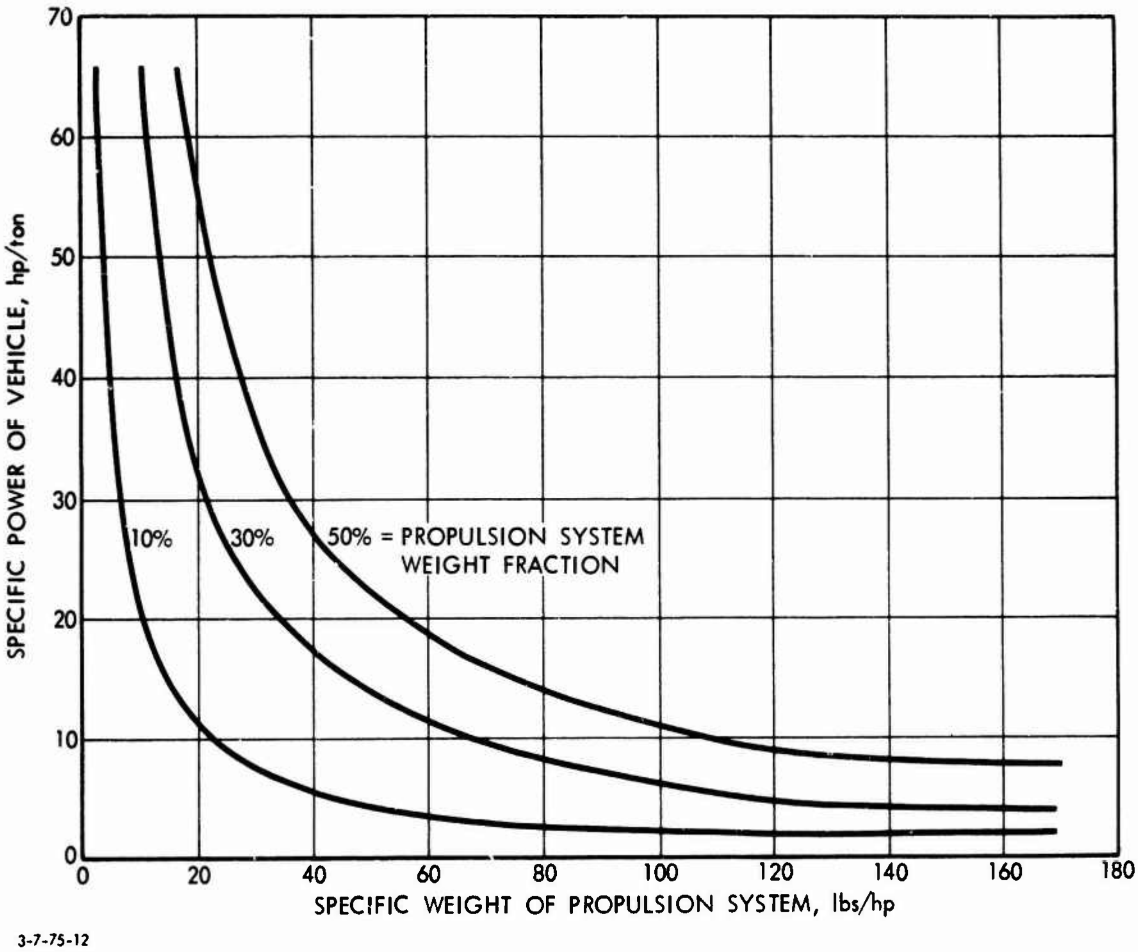

FIGURE 2.3. Propulsion System Specific Weight Limits

Rewriting Eq. (2.1) gives

$$E\left(\frac{P_e}{W_v}\right) = \frac{W_f}{W_v}\frac{1}{sfc} \quad , \tag{2.2}$$

or

$$\text{(Endurance)(Specific Power)} = \frac{\text{Fuel Weight Fraction}}{\text{Specific Fuel Consumption}} \quad .$$

For engines that use petroleum fuels, the specific fuel consumption under military operating conditions averages 0.5 lbs/hp hr ±20 percent. This number is fairly stable because all these engines are ultimately limited by the possible thermal cycle efficiency in converting fuel energy to mechanical energy, and all have been under development long enough to be reaching toward this limit. Using sfc = 0.50 and converting to convenient units, Eq. (2.2) then becomes

$$\begin{pmatrix}\text{Endurance}\\ \text{in Hours}\end{pmatrix}\begin{pmatrix}\text{Specific Power}\\ \text{in hp/ton}\end{pmatrix} \cong 4000 \begin{pmatrix}\text{Fuel Weight}\\ \text{Fraction}\end{pmatrix}^{*} \quad . \tag{2.3}$$

Thus, if the fuel weight fraction is fixed, the endurance varies approximately inversely with the specific power. Operational interest is in range rather than endurance, however, and that is the subject of the next section.

2.3 Range

The Services, while asking for greater mobility, would also like to maintain or increase the range of their combat vehicles. Unfortunately, mobility and range are conflicting requirements on the vehicle design. Many of the significant observations in this study arise from an examination of this conflict between mobility and range. In this section, the general nature of the problem will be considered.

*Using short tons for long tons, the constant is 4480. In general, short tons are used for land vehicles, long tons for sea vehicles.

It was shown in Eq. (2.3), that endurance is approximately inversely proportional to specific power. However, since range is endurance times speed, and speed increases with specific power, it is not immediately clear how range and specific power are related. A correct analysis involves a detailed consideration of how drag and propulsion efficiency vary with velocity for different types of vehicles. This is discussed in Appendices C, D, and E. For our immediate purposes it is sufficient to observe what has been attained in actual designs.

From Eq. (2.2)

$$(R)\left(\frac{P_e}{W_v V}\right) = \frac{W_f}{W_v}\,\frac{1}{sfc} \quad , \tag{2.4}$$

where

R = Range = EV

V = velocity at power P_e

and other notation is as before.

The term P_e/W_vV is the specific resistance. It is related to the more commonly used Lift/Drag (L/D) ratio as follows:

$$\frac{P_e}{W_v V} = \frac{DV}{\eta_{xt}\, W_v V} = \frac{1}{\eta_{xt}\, L/D} \quad , \tag{2.5}$$

where

η_{xt} = efficiency of the combined transmission and thruster

D = drag

L = lift = W_v

For the purposes here, it is more convenient to use specific resistance than L/D since it is applicable to all types of vehicles, whether they use static lift, are bouyantly supported, generate dynamic lift, or use thrust to produce lift. For the special case of sfc = 0.5, Eq. (2.4) becomes, in convenient units,

$$(\text{Range in nmi})\left(\begin{matrix}\text{Specific Resistance}\\ \text{nondimensional}\end{matrix}\right) = 650 \left(\begin{matrix}\text{Fuel Weight}\\ \text{Fraction}\end{matrix}\right) \quad . \qquad (2.6)$$

Table 2-3 shows estimates of range and endurance using Eqs. (2.3) and (2.6) for some familiar vehicles.

TABLE 2-3. ESTIMATED RANGE AND ENDURANCE FOR TYPICAL VEHICLES

Typical Vehicle	Specific Power (hp/ton)	Fuel Fraction	Estimated Endurance (Hr)	Estimated Range (nmi)
Experimental High-Speed Ship	100	0.30	12	700-900
Hydrofoil Cruising	50	0.30	24	1,200
SES Cruising	30	0.30	40	2,000
Experimental Tank	30	0.05	7	350
Destroyer - Top Speed	20	0.25	50	1,700
Battle Tank	20	0.05	10	300
Aircraft Carrier - Top Speed	3	0.10	133	4,700
Destroyer - Cruising	3	0.25	333	6,000
Aircraft Carrier - Cruising	0.5	0.10	800	14,000

These results are a first approximation to the familiar Breguet range equation which applies particularly to dynamic-lift vehicles and takes account of the change in drag due to the change in weight of the vehicle as fuel is used. Using the Breguet formula the simple ratio, fuel weight fraction in Eq. (2.4), would be replaced by the term

$$\ell n\left(\frac{W_v}{W_v - W_f}\right) = \ell n\left[\frac{1}{1 - (\text{fuel weight fraction})}\right] \quad . \qquad (2.7)$$

The difference between Eq. (2.7) and the fuel weight fraction alone is small at small values of fuel weight fraction, increases to 19 percent at $W_f/W_v = 0.30$, and then more rapidly as W_f/W_v gets larger. Most useful vehicles have fuel fractions of 0.30 or less, as is discussed in more detail in Appendix C.

The value of specific resistance as a measure of vehicle design is that it shows the efficiency with which a given vehicle can negotiate given terrain. It also answers the question of whether increased speed and reduced endurance will increase or decrease range. The answer is, for a given fuel load, if specific resistance increases as speed increases, then range will decrease [Eq. (2.6)]. Since specific resistance is proportional to the drag/weight ratio [for η_{xt} constant, see Eq. (2.5)], range will tend to decrease if the drag/weight ratio increases with velocity. On land, drag/weight is nearly independent of velocity, but for any vehicle that moves in a fluid, drag/weight generally increases with velocity. We may expect, therefore, that high-speed ships with petroleum fuels will have range limitations.

These implications are shown explicitly in Fig. 2.4 which is the same as Fig. 2.2 with lines of constant specific resistance added. No approximations are involved here since specific resistance is simply specific power divided by velocity. Using the approximation in Eq. (2.6) we can infer a range for each value of specific resistance. This shows that there is a strong tendency toward reduced range for high-speed ships. This range limitation is given more definitively in Fig. 2.5 which shows the approximate variation of power with speed between cruise and top speed conditions for oceangoing Navy ships (using data from Appendix D). It appears here that unconventional high-speed ships all have relatively high fuel consumption rates throughout the power range when compared to displacement ships.

2.4 Vehicle Size

So far, the limits that mobility and range requirements impose on the specific weights of propulsion systems have been considered. To determine the level of power that is required, it is necessary

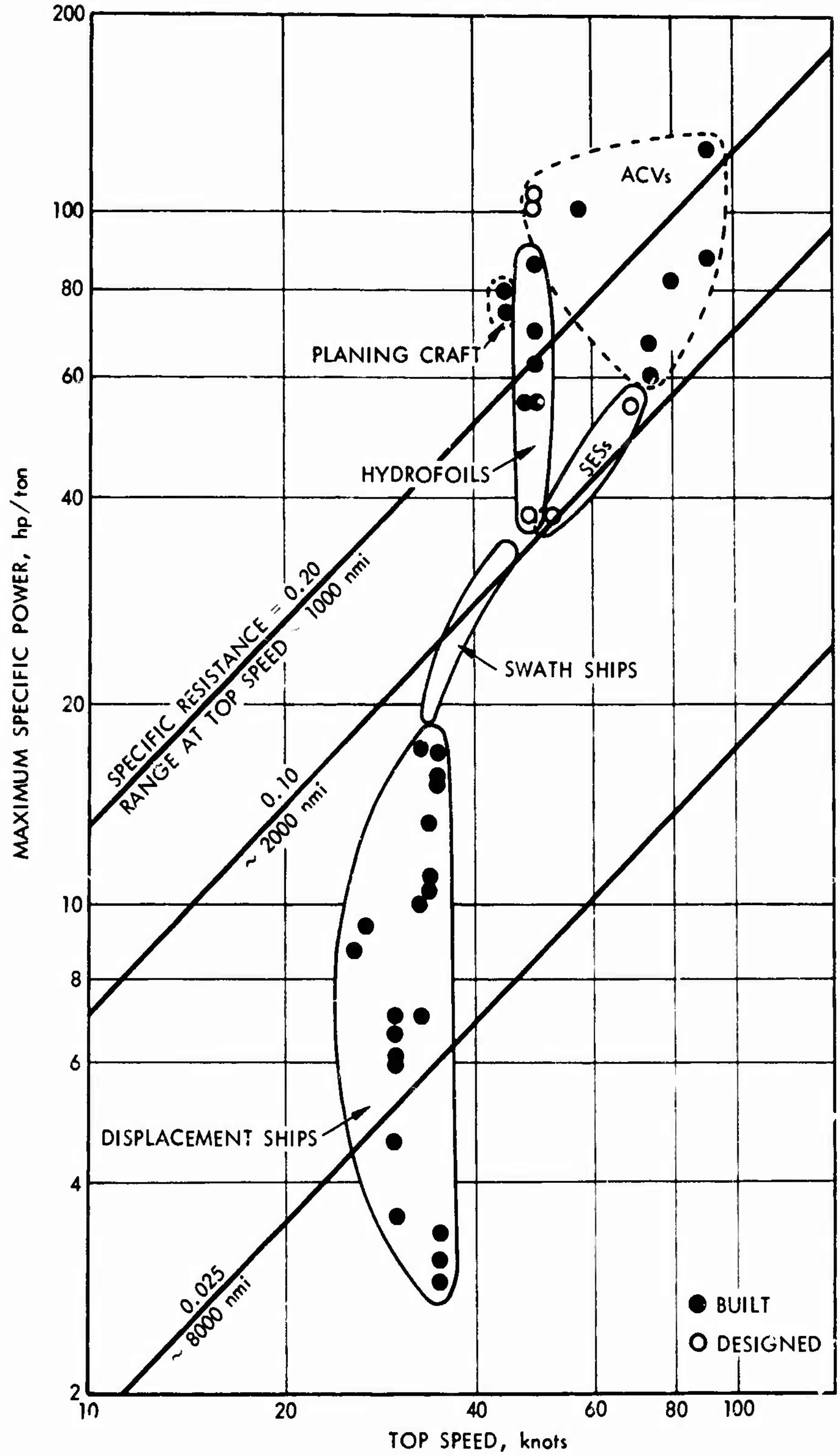

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FIGURE 2.4. Specific Power and Specific Resistance for Navy Ships

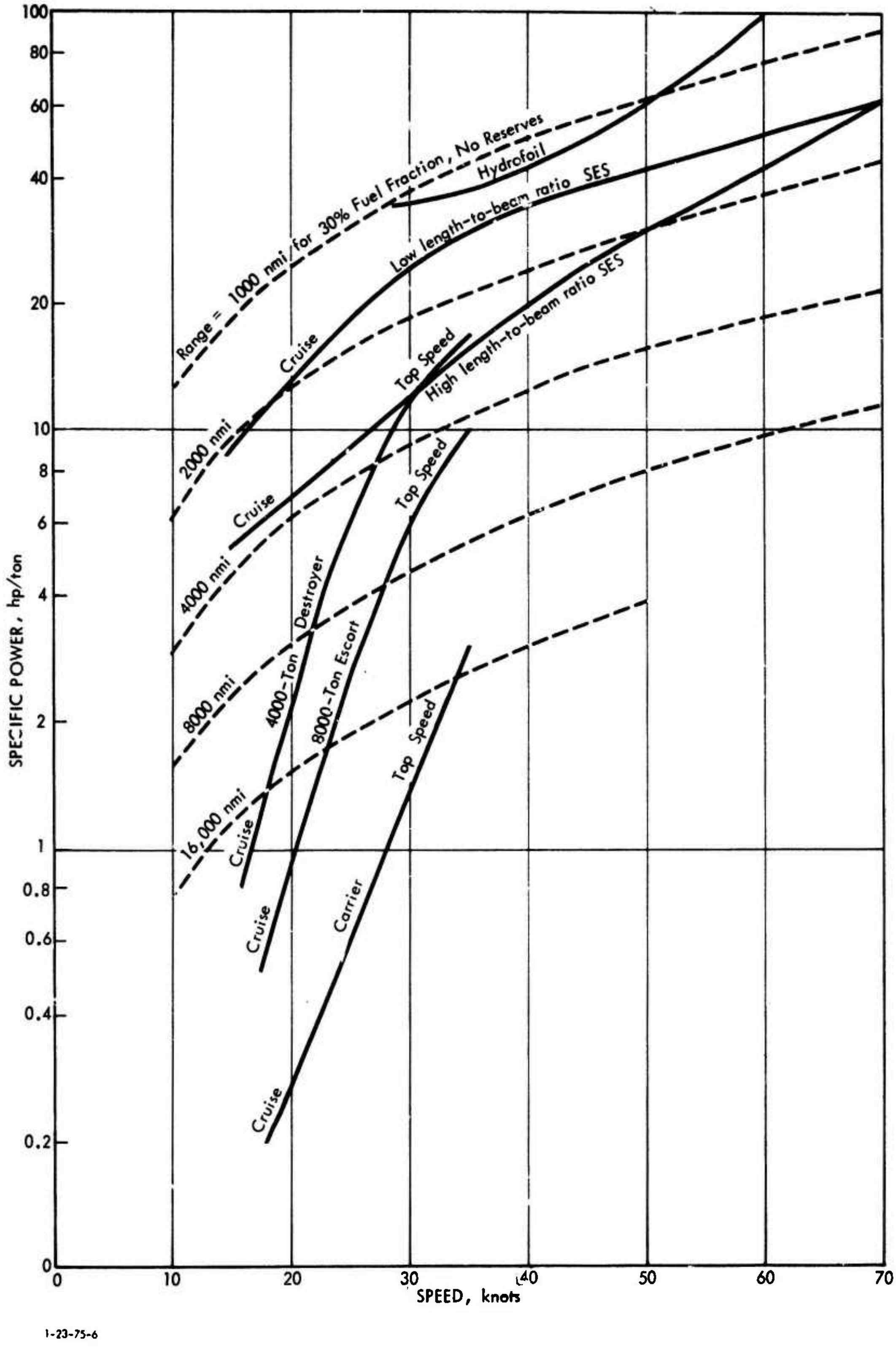

FIGURE 2.5. Specific Power/Range Relationships for Navy Ships

now to establish overall size limits for different classes of vehicles. There are two constraints on size, one based on physical considerations, the other on costs.

2.4.1 Physical Limits

There is an ultimate limit on the size of land vehicles* that must operate on unprepared surfaces. It is caused by the increase in ground pressure as the vehicle gets larger and by the limited ability of soils to bear this pressure. If a given design is simply scaled up in size, the area of ground contact increases as the scale factor squared, while the weight increases as the scale factor cubed. Thus, the ground pressure increases linearly with the scale factor. It has been estimated that there is a practical limit of about 120 tons in tracked vehicles, and these would have limited mobility, since the large surface contact area impedes turning.

The heaviest military land combat vehicles in general use are the U.S. and British Main Battle Tanks (MBTs) which have reached about 60 tons. Future trends are toward lighter tanks to provide greater mobility. Other armored combat vehicles generally fall in the range 20 to 40 tons. High-mobility support vehicles range up to 20 tons in gross weight.

There do not seem to be any reasons or prospects for these weight ranges to change in future vehicles, except where armor is a large percentage of the payload. The prime example of this is the MBT where armor is nearly half the gross weight (though it performs as structure also). In such vehicles, appreciable weight reductions can be made without sacrificing armor protection if the volume of the protected payload can be reduced.

For ocean vehicles, the situation is more complex. The effect of variations in size is quite different, depending on whether the

*A vehicle is a single unit, as distinct from a train of units which, in principle, could be any length.

vehicle is a displacement ship, a dynamic lift vehicle (e.g., a hydrofoil), a powered lift vehicle (e.g., an ACV or SES), or a submarine.

The effect of size in displacement ships is shown in Fig. 2.6, which shows specific power, length, and top speed of all Navy combat ships built since the early 1950s. The significant observation is that to maintain a top speed of 35 knots there is a large reduction in specific power requirements as displacement ships get larger. The reason is that the greatest drag component at this speed is wave drag, which depends on Froude number, i.e., the length of the ship relative to the length of a gravity wave traveling at this speed (see Appendix D for more detailed discussion). As specific power requirements increase, range tends to decrease as noted above and the destroyer of about 4000 tons is the smallest practical size that can cross the Atlantic Ocean at high speed (see Table 2-3 and Fig. 2.5).

The significant effect of size in hydrofoils is in the increase in weight of the foil as the size increases. This is typical of any dynamic lift vehicle since the lift is proportional to the area of the lifting surface* and the weight to the volume. There is a similar, but less pronounced, size effect on ACVs and SESs which shows itself in increased cushion pressure as the vehicle gets larger. Hydrofoils are developing serious foil weight problems at 1500 tons gross weight; ACVs structural weight percentages get excessive by 1000 tons; and low L/B SESs have practical cushion pressure limits which cause serious design problems above about 5000 tons.

The trend in SES design has been to a high L/B configuration which lessens the structural problem in large SESs and reduces the losses associated with high cushion pressures. As a result, there is no simple way to set an upper limit on the size of a high L/B SES. There seems little doubt, however, that a size limitation will appear depending on the L/B ratio, when more detailed designs are made.

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*There is a practical "wing loading" limit due to cavitation (see Appendix D).

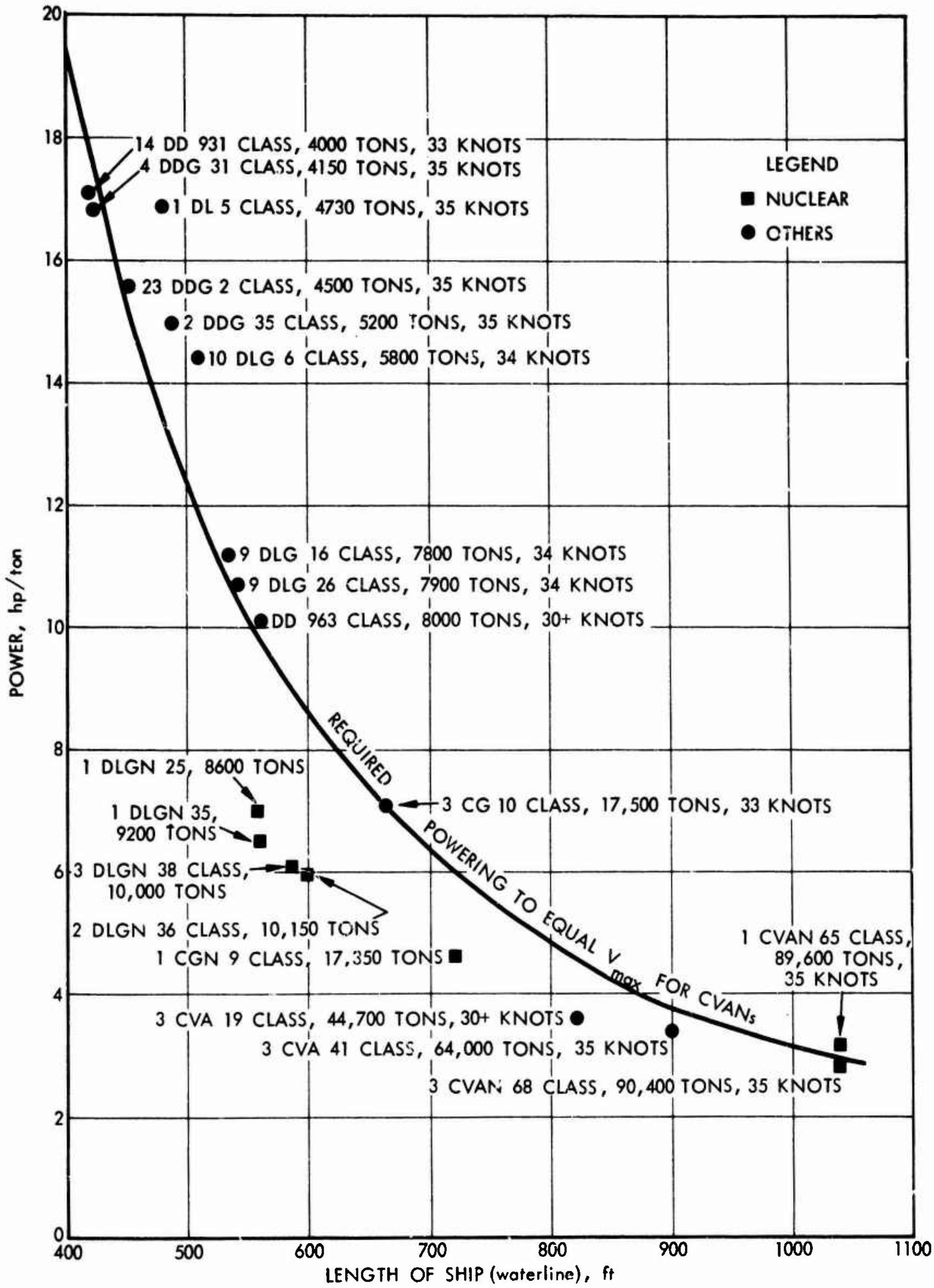

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FIGURE 2.6. Powering of Modern Navy Ships

The point of this discussion is not that there are sharp cut-off points in size for different vehicles, but rather that the design of practical military vehicles with acceptable weight distributions (see Appendix C) gets progressively more difficult as the vehicle gets larger. For the purposes of estimating maximum total power requirements, the upper limits of size for military vehicles is shown in Table 2-4. Note that vehicles which depend on their volumes to support their weight do not have the same physical size limitations as vehicles which generate lift over an area.

TABLE 2-4. UPPER LIMITS OF SIZE FOR SOME MILITARY VEHICLES

Vehicle Type	Maximum Size for "Practical" Vehicles
Area Lift	
Hydrofoils	~ 2000 Tons
ACVs	~ 1000 Tons
SESs - Low L/B	~ 5000 Tons
- High L/B	~ Unknown
Planing Boats	~ 500 Tons
Tracked Vehicles	~ 100 Tons
Wheeled Vehicles (off-road)	~ 40 Tons
Volume Lift	
Displacement Ships	No practical limits for military needs
Airships	No practical limits for military needs
Submarines	No practical limits for military needs

2.4.2 Cost Limits

Cost cannot impose any absolute limits in projecting future needs until ways are found to establish meaningful cost-effectiveness measures in cost/performance trade-offs. However, cost is of value in making relative judgments for the guidance of Technology Base programs. In this vein, a generalized method of estimating vehicle acquisition costs is developed in Appendix C. It is shown there that cost estimates can be based on a formula of the form

$$\frac{\$}{\text{Vehicle}} = \begin{array}{c}\text{Cost element}\\ \text{based on weight}\end{array} + \begin{array}{c}\text{Cost element based}\\ \text{on specific power}\end{array} \tag{2.8}$$

which takes the explicit form

$$\frac{\$}{\text{Vehicle}} = W_v \left[1000 \frac{W_o}{W_v} + Q^{-0.33}\left(1200 \frac{P_e}{W_v}\right)\right] \tag{2.9}$$

where

W_v = gross weight of vehicle in tons

W_o = empty weight of vehicle in tons

Q = number of vehicles built

P_e/W_v = specific power in hp/ton

It should not be assumed from the nature of the terms that the first term in Eq. (2.9) is a structural cost and the second is a powering cost. For very-low-powered vehicles this is approximately true, but for a vehicle with high specific power, the second term also includes the cost of strengthening the structure and reducing its weight to accommodate the higher loads associated with higher hp/ton vehicles.

This formula will approximate the acquisition costs of a wide variety of vehicles from aircraft carriers to trucks (see Appendix C). Its most interesting feature is the dependence on specific power. In fact, for vehicles with specific power greater than 10 hp/ton (which includes essentially all high-performance surface vehicles) the cost equation may be approximated by

$$\frac{\$_v}{W_v} = 1200\, Q^{-0.33} \frac{P_e}{W_v} \tag{2.10}$$

i.e., the vehicle cost per ton is directly proportional to the specific power. This provides a useful rule of thumb in estimating the price of mobility since mobility is directly determined by specific power (see Section 2.2).

It is most useful to relate costs to the payload, since the military requirement is fundamentally to provide a given payload with a given mobility over given terrain. Of necessity, vehicles carry structure, fuel, and propulsion systems in addition to payload, but this function is costly and nonproductive. In terms of cost per ton of payload*, Eq. (5.3) becomes

$$\frac{\$_v}{W_p} = \frac{1200\ Q^{-0.33}\ P_e/W_v}{W_p/W_v} \quad . \tag{2.11}$$

Thus, the payload fraction, W_p/W_v, is an important factor in determining cost-effectiveness. Vehicles with low payload fractions are costly to acquire and to operate. For high-performance vehicles, payload fractions of 20 percent to 50 percent have proved practical. If the payload fraction gets below 20 percent, alternatives should be examined.

Two cases of interest here may be considered, (1) the cost of a large high-performance vehicle and (2) the cost of using a high-performance vehicle at its extreme range. As an example of the first case, consider the 10,000-ton SES escort which has been cited as a goal of current development work. It will require a propulsion system of about 500,000 hp. This is twice the power of a carrier and hence the 10,000-ton SES would cost about twice as much as a carrier by this analysis. Thus, though there were no clearly defined physical limits on the size of a high L/B SES, there may well be cost limits.

An example of the second case, i.e., using a high-performance vehicle at its extreme range, is an ocean-crossing hydrofoil. One

*See Appendix C for a definition of payload.

such design carries about 45 percent of its weight in fuel and has a payload of about 6 percent. The cost difference between this 50-knot vehicle and a 40-knot displacement ship carrying a 20 percent payload appears as a factor of 4 or 5.

2.5 Implications for Propulsion R&D

The purpose now is to examine the implications of the military needs outlined above on the propulsion system. The goal is to determine what ranges of total power and of specific weights and volumes of propulsion systems are needed by military vehicles. This information can then be used for evaluating the military potential of the numerous powering options that are available.

First, the total propulsion power for different types of vehicles can be obtained from the specific power requirements (Section 2.2) and the vehicle size requirements (Section 2.4). Thus, for its high-performance vehicles, the Army needs power plants in the range of 100 hp to 2000 hp; while the Navy needs 70,000 hp to 300,000 hp for its ocean vehicles and 6000 hp to 15,000 hp for coastal patrol ships. It is interesting to note that while the specific power requirements for both land and ocean vehicles fall in the same range, the ocean vehicles are roughly two orders of magnitude heavier than land vehicles and hence require power plants two orders of magnitude larger. For this reason alone, it is to be expected that there would be little overlap in Army and Navy propulsion system developments.

The remainder of the discussion in this section concerns the weight and volume that can be assigned to the propulsion system. A preliminary vehicle design can be made knowing only the specific weight and volume of the power train together with the specific fuel consumption of the system. By reversing this process, i.e., looking first at the vehicle design, the required characteristics of the propulsion system can be determined.

In following this line it is necessary to distinguish between weight-limited and volume-limited vehicles. By definition, a weight-limited vehicle is one in which the total drag is more strongly dependent on changes in weight than in volume. In a volume-limited vehicle, the reverse is true. Most actual vehicles are neither completely weight- nor volume-limited, but many are dominated by one consideration. An example of a weight-limited vehicle is a hydrofoil or an ACV. A fleet submarine is volume-limited, but special-purpose, deep-diving submarines become weight-limited. The reason for this change is that the pressure hull becomes very heavy for deep dives, and the average density without payload eventually exceeds that of sea water. Whether vehicles are weight- or volume-limited is of importance largely in considering alternative fuels (e.g., liquid hydrogen) where large density changes must be considered. For engines, transmission, and thrusters, average densities remain remarkably constant, and so weight and volume changes are closely tied to each other.

Table 2-5 classifies the vehicles of interest here with some others as illustrative examples according to how they generate lift and whether they are weight- or volume-limited.

TABLE 2-5. WEIGHT- AND VOLUME-LIMITED VEHICLES

Vehicle Type	Weight-Limited	Volume-Limited
Static Lift	Trucks Lightly Armored Vehicles	Tanks
Buoyant Lift	Airships	Submarines
Dynamic Lift	Hydrofoils Planing Boats	Cruise Missiles
Powered Lift	ACVs SESs Helicopters	

Within this framework, and using typical design data,* we can examine each of the vehicle classes of interest and arrive at the characteristics that are required to be met by the propulsion systems. The results are shown in Table 2-6.

*See Appendix C.

TABLE 2-6. PROPULSION SYSTEM NEEDS

Class of Vehicle	Projected (hp/ton)	Approximate Weight (tons)	Propulsion System Requirements Power Range hp	Total Weight* lbs/hp	Volume ft^3/
LAND					
Tank	25-50	50	1,200-2,000	12-6	0.08-0.05
APC	20-50	10-20	200-1,200	20-8	-
SP Gun	20-40	10-30	200-1,200	20-10	-
Goer-type	10-20	20	200-400	30-15	-
Gama Goat-type	20-30	5	100-150	15-10	-
OCEAN					
Destroyer	18	4,000	72,000	40	0.08
Escort	10	8,000	80,000	50	0.10
Carrier	3	90,000	270,000	150	-
High-Speed Escort	50-60	2-5,000	100-300,000	18-15	-
Submarine	2-3	6-7,000	12-20,000	130	0.05
COASTAL					
CPIC	80	75	6,000	9	-
PG 84	75	225	15,000	10	-
SSP	34	190	6,400	20	-
SPECIAL					
Ship-to-Shore ACV	100	180	18,000	5	-

*Fuel is included but for land vehicles suspension and running gear (~20 percent of gross weight in tracked vehicles) is not included.

3. TECHNOLOGY POTENTIAL

3. TECHNOLOGY POTENTIAL

3.1 General Considerations

The purpose of this section is to sort through the characteristics of all the available propulsion system components to identify those with the greatest potential for meeting military needs. The general criteria established in Section 2 will be useful in this selection process. To reach meaningful results, it is necessary to establish how the component characteristics vary with size and a rationale for where improvements may be expected. This information has been gathered from numerous sources and, where it is extensive, it is presented in Appendices.

Before considering each component in turn general observations can be made. The first is that, contrary to expectations, propulsion systems do not benefit from increasing size in terms of weight and volume requirements. On the contrary, power tends to be area-dependent while weight is volume-dependent, causing both specific weight and specific volume to go up as propulsion power increases. This is shown explicitly for internal combustion engines in Appendix F. It is mentioned here only because it is the opposite trend to what one intuitively expects from "economy of size" arguments. In fact, it can be categorically stated that there is no real economy of size effect in propulsion systems--both specific weight and volume tend to increase with size beyond a certain point.* The second general observation is that the specific cost ($/hp) of propulsion systems tends to remain constant as size increases. The rationale for this is that basic material costs, which are volume-dependent, are relatively small. The major costs are associated with machining and fabrication processes which are area-dependent. Since power is also area-dependent, cost per unit power remains constant.

The final observation is that, except for nuclear engines, propulsion systems are technically mature in the sense that no major

*In nuclear propulsion systems, the dominance of the shielding weight masks this trend at power levels of interest here (see Appendix G).

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innovations have appeared for many years. By major innovation, we mean a new device which is such an advance that in a short time it completely replaces all competition. Recent major events have been

- The gas turbine for aircraft propulsion
- The diesel/electric drive for locomotives
- The automatic transmission for automobiles.

We may expect, therefore, that the greatest technological advances in improving propulsion system components have already been made. The greatest opportunities will probably lie in transferring to new uses, e.g., gas-turbine-powered ships and tanks. One exception is the nuclear engine which is in its infancy in propulsion applications.

3.2 Combustion Engines

Internal combustion engines include those in which combustion takes place inside the working fluid, as distinct from external combustion where heat is transferred to the working fluid through a heat-transfer surface. Spark ignition, diesel, rotary, and gas-turbine engines are internal combustion engines of interest here. Stirling and Rankine cycle engines and conventional steam turbines are external combustion engines.

The attainable specific weights of internal combustion engines as a function of power are examined in Appendix F, with the results indicated in Fig. 3.1. As noted above, all types show an increase in specific weight as power increases, because of the volume/area-dependence of weight/power. At small power levels, there is also a weight increase due to increased heat losses. As a result, each has an optimum size with respect to specific weight. Since engine densities remain nearly constant for each type, specific volumes follow the same trends as specific weights.

Figure 3.1 shows that techniques which increase the air flow through a given volume (e.g., supercharging) will reduce specific weight. Other techniques for reducing exhaust waste (e.g., turbo-compounding) will also reduce specific weight. These techniques change

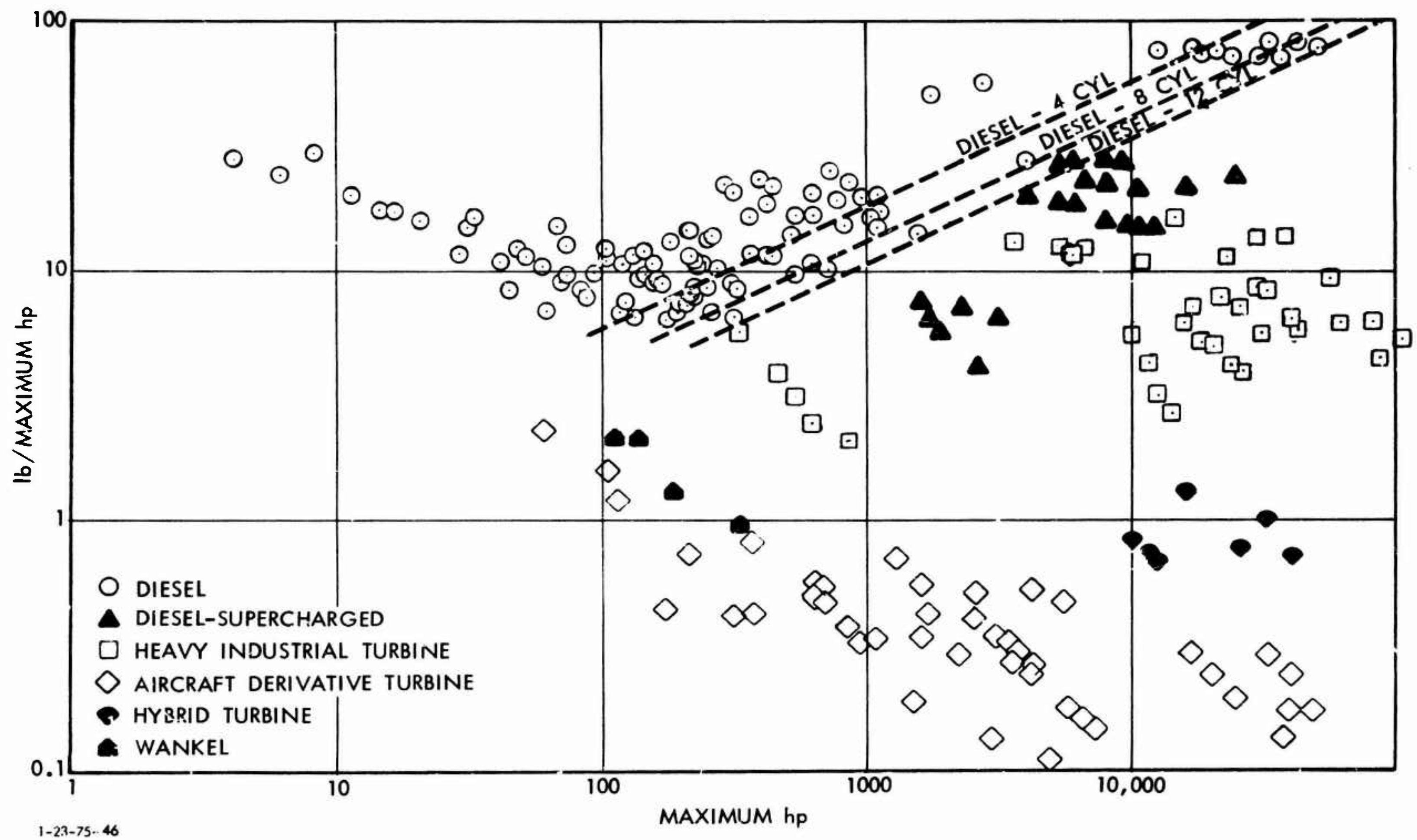

FIGURE 3.1. Specific Weight of Internal Combustion Engines

the levels shown in Fig. 3.1 but do not change the power level optimums appreciably. These and other approaches for getting more power out of a given engine are discussed also in Appendix F. From this analysis, together with the bounds established on propulsion system weights, (Table 2-6 and Appendix C), it is possible to make an initial selection of engining possibilities for the vehicles of interest here. Such a selection is shown in Table 3-1.

TABLE 3-1. COMBUSTION ENGINE POSSIBILITIES FOR MILITARY HIGH-PERFORMANCE VEHICLES

Vehicle	Power Range (hp)	Possible Engine	Specific Weight (lbs/hp)
40-60 Ton Tracked	1,200	Diesel-supercharged	6-7
	2,000	Diesel-turbocompound	8-10
	1,000-2,000	Turbine	1-2
10-40 Ton Tracked	200-1,200	Diesel-supercharged	3-6
	400-1,200	Turbine	2
	200-400	Rotary	2-3
	200-400	Spark Ignition	2-4
4,000-8,000 Ton Escort	60,000 to 80,000	Steam Turbine	13-15
		Gas Turbine	1-2
High-Speed Escort	80,000 to 300,000	Gas Turbine	1-2
High-Speed Coastal	6,000 to 15,000	Diesel-supercharged	10-20
		Gas Turbine	1-2
Short-Range ACV	18,000	Gas Turbine	1-2

Note that the only external combustion engine in Table 3-1 is the 60,000- to 80,000-hp steam turbine. Both Rankine-cycle and Stirling-cycle external combustion engines have been used experimentally in automobiles. However, they suffer from inherent weight and volume problems due to the necessity of transferring all the energy into and out of the working medium through heat exchangers. They cannot meet the weight and volume requirements of high performance military land vehicles.

3.3 Nuclear Engines

Nuclear engines are considered separately because, on a weight and volume basis, they must be compared to the combined engine/fuel requirements for combustion engines. It is clear at the outset that for range-limited vehicles, nuclear propulsion is the ultimate answer. The problem for military high-performance vehicles is that the current state of nuclear engine development requires specific weights of over 100 lbs/hp. Reference to Table 2-6 will show that on this basis nuclear propulsion is limited to large surface ships and submarines. The basic technology question is, therefore, what are the prospects for reducing weight and volume requirements for nuclear engines?

This question is examined in Appendix G using information from the development of nuclear propulsion systems for nonmilitary ships. It appears that the major physical block to reduced weight is shielding. Shielding weight can be reduced by different physical arrangements which, however, infringe on current military standards for accessibility and ruggedness. One may expect that these deficiencies will gradually be solved by trial and error.

The general picture that evolves is shown in Fig. 3.2. Nuclear propulsion could become attractive for conventional escorts with moderate technological advances as discussed in Appendix G. However, a major step to high-temperature gas-cooled reactors is needed to meet the stringent weight requirements for high-speed escorts.

3.4 Transmissions

3.4.1 Conventional Types

Mechanical, hydrokinetic, and hydromechanical types of transmissions are considered to be conventional. The technology for all these types is developed to the point where most new requirements can be met by modification of existing systems or components.

For land vehicles, military needs are for both wheeled and tracked vehicles. The latter have more complicated transmission systems because a steering capability is incorporated in the power transmission

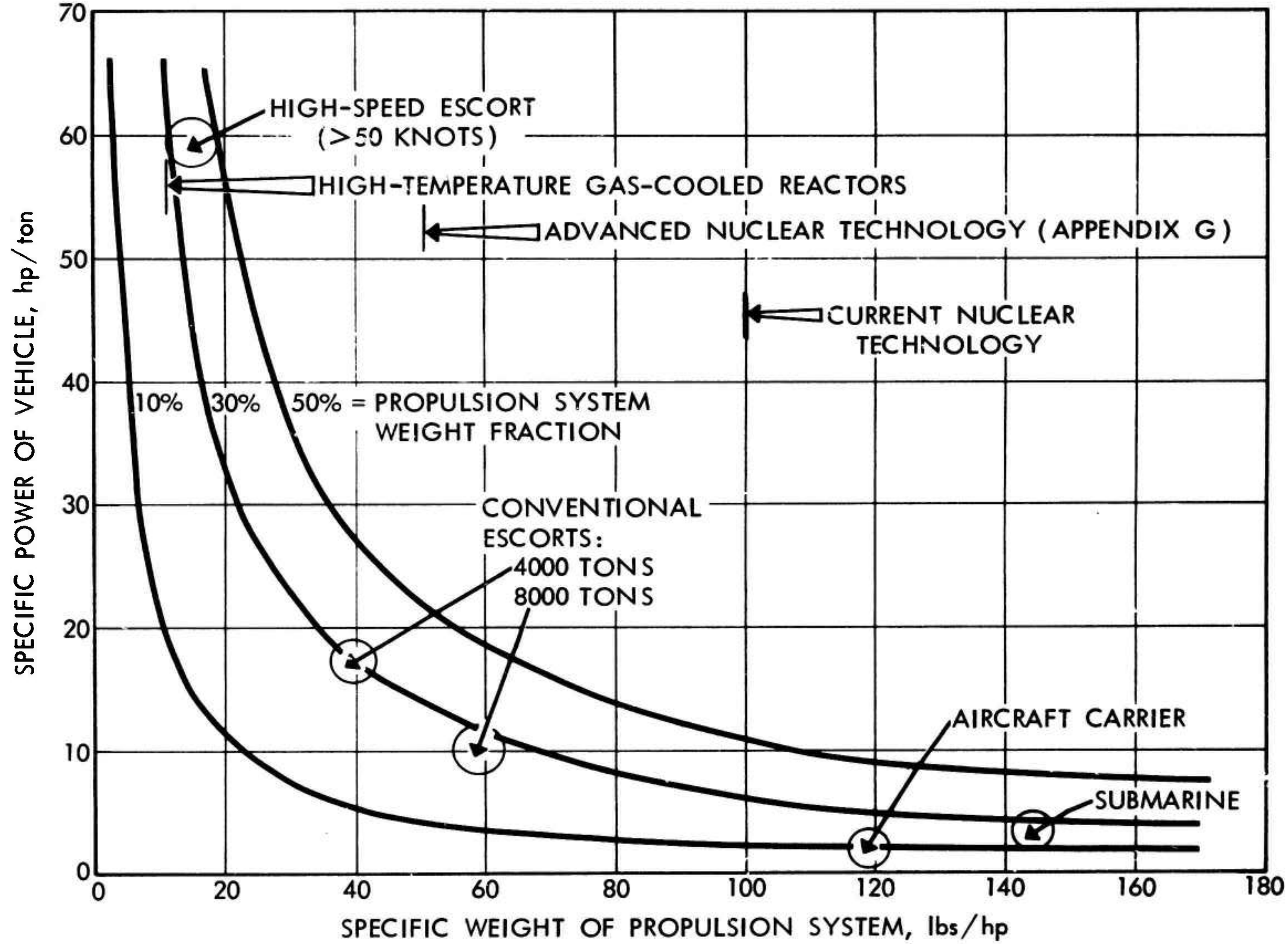

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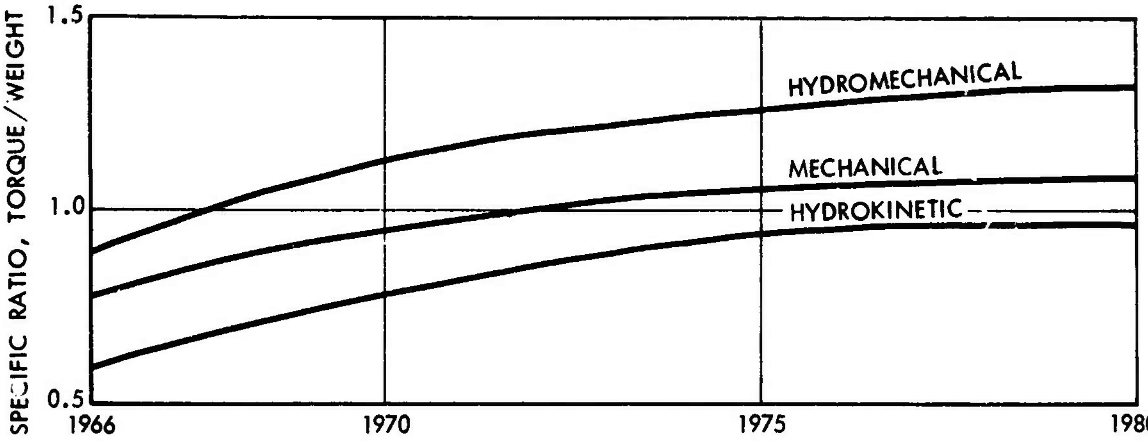
FIGURE 3.2. Nuclear Propulsion Prospects

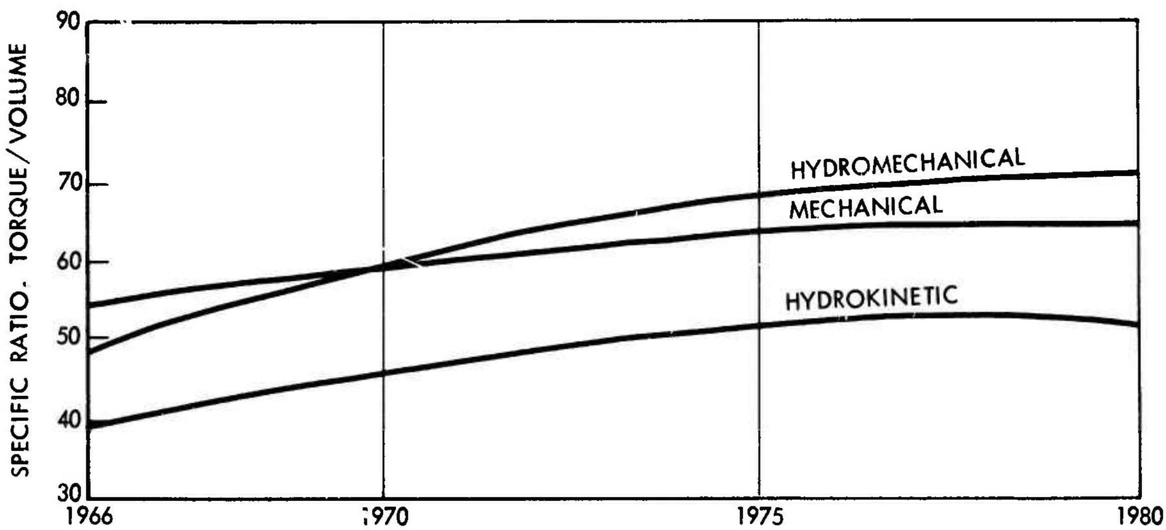
requirements. Great improvements have been made since the early mechanical systems with the introduction of hydrokinetic and, more recently, hydromechanical systems. Trends in torque/weight and torque/volume ratios for these systems show that few improvements are to be expected in the future (see Fig. 3.3). This further confirms the mature position of this technology. In general, it appears that future requirements for high-performance land vehicles can be met by conventional transmission systems within the bounds of existing technology.

For sea vehicles, the custom has been to use extremely conservative transmission design to get the ultimate in ruggedness and reliability. This, combined with high power and relatively low rotational speeds makes heavy transmissions systems. As long as engines were heavy (e.g., oil-fired boilers and steam turbines or large diesels) the weight of the transmission system was not of crucial importance. However, the shift to high-speed ships with gas-turbine engines has forced a revision in this custom. Fortunately, the technology for reducing transmission weights (more highly stressed gears, different types of gears, etc.) was available from other sources. As a result, the designers of high-speed ships have been able to get transmission systems at acceptable weights, even in difficult transmission path situations. For example, a transmission system of 0.8 lbs/hp to 1.0 lbs/hp was estimated for a 50,000-hp installation in a large SEV with power being delivered to eight fans and two propellors from two engines (Ref. 6). In another 80,000-hp design for a SWATH ship, a transmission weight of 3 lbs/hp was estimated. Similar specific weights apply to the 2000-ton SES designs.

Thus, as for land vehicles, it appears that demands for high-performance sea vehicles can be met from existing technology though systems of this size have not actually been built and tested yet. The high power levels and multipoint distribution requirements of high-speed ships do make conventional transmission systems relatively heavy compared to gas-turbine engines, so there is some pressure for lighter and more flexible systems in the range of 40,000 hp and up.



a. Torque/Weight



b. Torque/Volume

Source: Engine-Transmission Power Plants for Tactical Vehicles, AD 821500L, Research Analysis Corporation, Report RAC-R-26.

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FIGURE 3.3. Power-Train Development Trends

3.4.2 Electrical Types

Electric transmissions for land vehicles are well developed in commercial use but not in forms directly applicable to Army needs. Locomotives and large mining trucks, in particular, have found direct current electric transmissions better than mechanical/hydraulic systems. As a result, a commercial technology has been created. The common factor in these vehicles is the need for large torque at low speeds which favors dc electric motors. This technology can be applied to some Army requirements as has been pointed out many times (Refs. 7 & 8). Several experimental vehicles have been built using dc drives both in this country and Europe. The application has generally been to heavy, high-mobility, wheeled transport vehicles which benefit greatly from all-wheel drive.

The basic problem in applying dc drives to high-performance vehicles is the weight of the motors which, in general, precludes them being mounted on the unsprung part of the structure. Hence, an additional "conventional" transmission is needed to transfer power to the thruster. The argument is often advanced that this destroys the advantages of electric transmission. On the other hand, the problem of linking the motor to the thruster is open to design ingenuity, and simple solutions seem possible (Ref. 8).

The other approach to electric transmission for land vehicles is to use ac drives. This allows immediate reduction in the weight of the motors but complicates the control problem. As with dc drives, there have been a number of experimental wheeled vehicles built. In the late 1960s there was also an intensive effort made to develop an ac electric drive for tracked vehicles. All these ac systems had serious problems with the solid-state power control equipment, which prevented reaching acceptable reliability standards. As a result, all these efforts were discontinued.

As noted above, foreseeable demands in high-performance land vehicles can be met with conventional transmissions. However, there are applications (e.g., multipoint power distributions) where electric transmissions look attractive. The potential for advances in technology which would affect weight, reliability and cost factors exists in both dc and ac systems. For ac systems, the state of the art in high-power, solid-state devices is advancing rapidly and one would expect that acceptable power-conditioning controls will eventually be available. In the dc area, lightweight motors are being developed and commercial applications for dc drives are expanding. In this environment, it would seem prudent to keep monitoring the Army applications for electric drives through continuing Technology Base activities.

For sea vehicles, the very high level of power transmission makes electric drives extremely heavy. To achieve the necessary weight reductions requires going to superconducting electric motors. This necessitates cryogenic cooling devices which make the overall system expensive and elaborate. In developing high-speed ships, however, there is a universal problem in power transmission paths and the flexibility of electric transmission is attractive. The technology of high-power superconducting motors is in its infancy and hence the potential for innovations and improvements is large. For these reasons, this field is one of significant potential for Navy Technology Base activities.

3.5 Thrusters

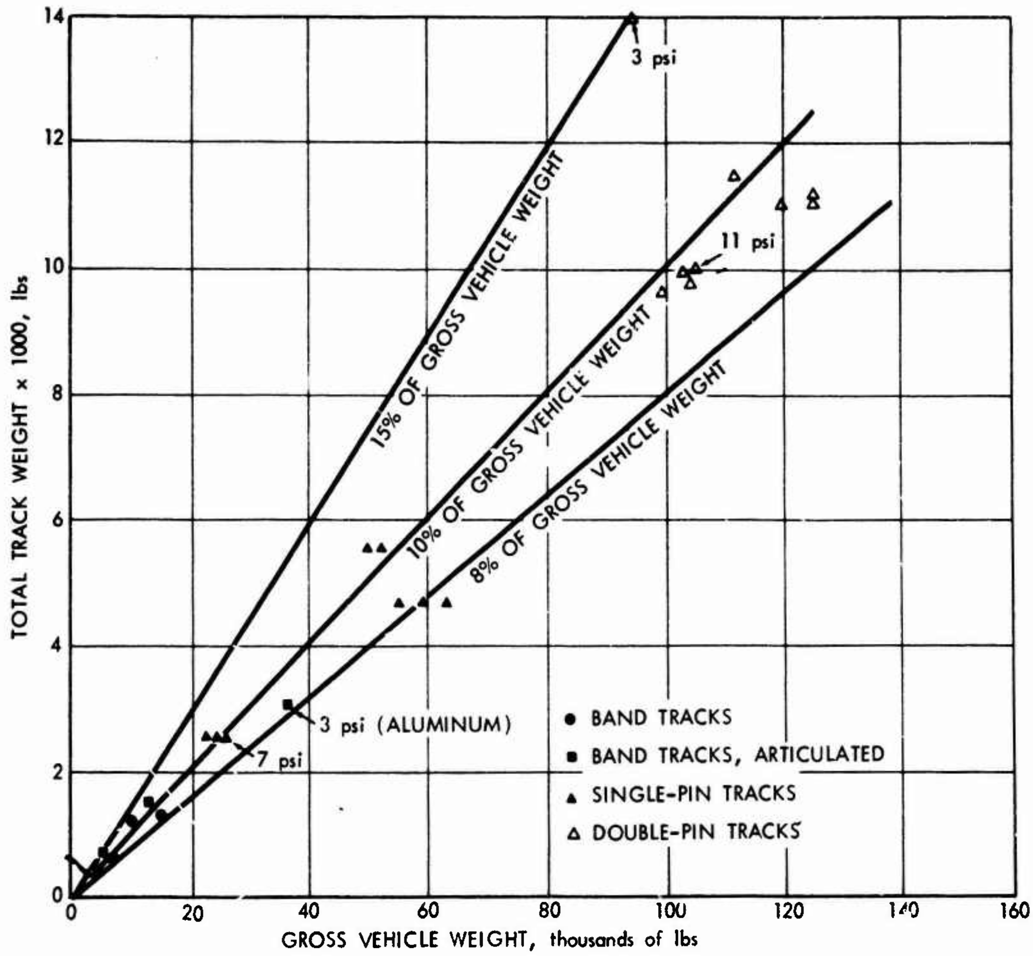
3.5.1 Land Vehicles

The only thrusters for land vehicles in extensive use are the track and the wheel. In terms of ability to couple with the terrain in off-road conditions, the track is far superior, not only because of its greater contact area but also because the tractive effort is strongly dependent on the length of the contact in the direction of motion (see Section E.5 of Appendix E). The disadvantage of the track is its weight, which puts heavy demands on the suspension system. The large unsprung weight in the track limits its use to heavy vehicles and even there the top speed in rough terrain may be limited by human tolerance to the roughness of the ride. For these reasons, in high-mobility vehicles, tracks are generally used for the large and/or slower moving vehicles and wheels for the smaller and/or faster ones. When wheels are used for off-road conditions, their reduced tractive ability makes all-axle drive a practical necessity. Figures 3.4, 3.5, and 3.6 show the relative weights of tracks and wheels, as demonstrated by design practice.

Improving off-road tractive capability of wheeled vehicles is a constant goal of inventors. One approach is to articulate the vehicle so as to optimize wheel contact area (e.g., the XM 808). Another is to drive each wheel separately and control the applied torque to keep each wheel at the same slip point. Each of these methods makes appreciable improvements in tractive ability under certain terrain conditions.

Another class of potential improvements is in unconventional thrusters. These efforts are generally directed at increasing traction in loose and wet soils. As discussed in Appendix E, soils lose their cohesion when they are ploughed or as they get wet, and this can stall even tracked vehicles. It is possible to design other types of thrusters which are better adapted to these conditions in which the soil begins to take on properties more like a liquid. Many of these have been proposed and some built and tested. However, none has received general acceptance. One apparent reason for these failures is the inability of the unique types of thrusters to match the performance of track or wheel over the wide range of operating conditions demanded of a high-performance Army vehicle.

The conclusion from this discussion is that high-mobility vehicle demands in thrusters are apparently being met by track and all-axle driven wheels. The potential for increasing traction in certain operating conditions by unconventional means exists but the need for this improvement has not been clearly established (see Appendix E).



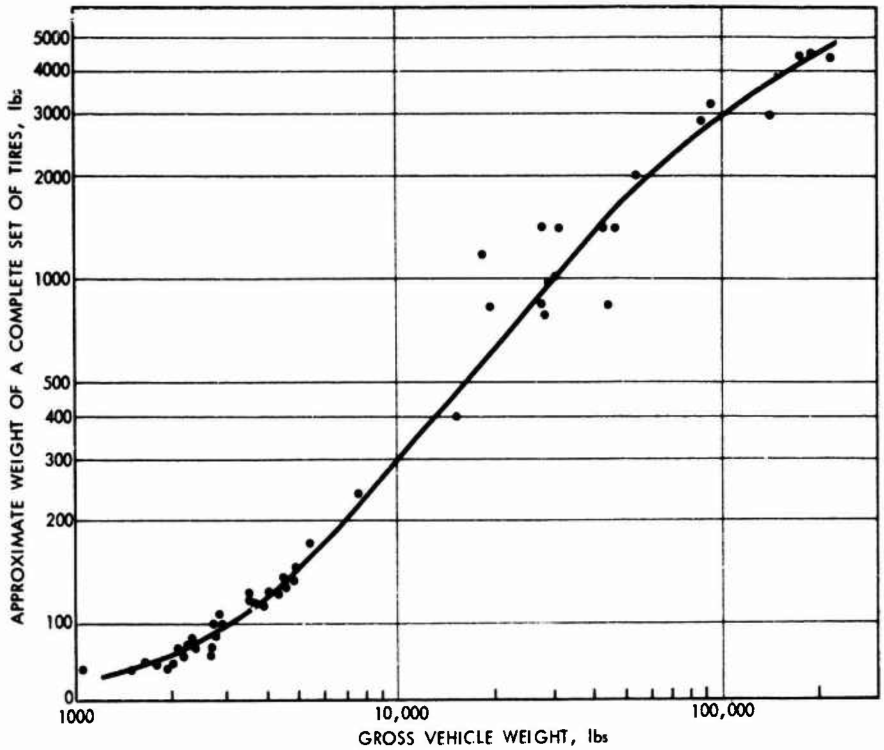
Source: "Introduction to Terrain-Vehicle Systems", M. G. Becker, University of Michigan Press, 1969.

1-23-75-11

FIGURE 3.4. Weight of Tracks

3.5.2 Sea Vehicles

The conventional thruster for sea vehicles is, of course, the propellor, which is unexcelled at subcavitating speeds. The main question for technology is how to provide efficient thrusters for high-speed ships (>50 knots). This problem has received considerable attention in recent years and a full range of possible solutions has been addressed. These include supercavitating propellors, water-jets, and a variety of water-/air-jet mixtures.



Source: "Introduction to Terrain-Vehicle Systems", M. G. Becker, University of Michigan Press, 1969.

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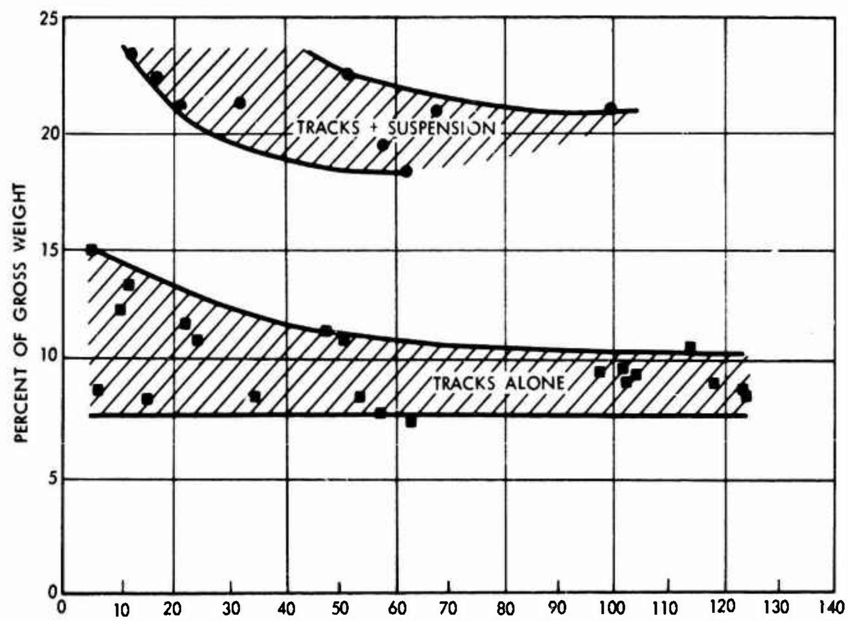
FIGURE 3.5. Weight of Wheel



Source: "Introduction to Terrain-Vehicle Systems", M. G. Becker, University of Michigan Press, 1969.

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FIGURE 3.6. Weight of Track Including Suspension System and Track Alone

If water is used as the propulsive medium, the basic problem is that at speeds over 50 knots, cavitation occurs readily at inlets or on the low-pressure side of the blade. If air is used as the propulsive medium, a huge thrust area is required to keep the exhaust velocity low enough to reach acceptable propulsive efficiencies. A review of two-phase propulsion systems is given in Ref. 9, which also provides a list of references on this subject. The water-jet propulsor is considered in Ref. 10 and the supercavitating propellor in Ref. 11. A general conclusion that appears from these studies is that high-speed propulsors will not match the efficiency of the subcavitating propellor. Of the high-speed devices considered, the supercavitating propellor and the water-jet show the most promise. In the experimental high-speed ships that have been built (Appendix B) and recently designed (e.g., 1300-ton hydrofoil and 2000-ton SES designs) the water-jet has been the preferred thruster, though efficiencies of 50 percent to 55 percent are the best yet reached.

It appears from a Technology Base viewpoint that there is considerable potential for improvement in both efficiency and weight of high-speed thrusters. Water-jets and supercavitating propellors appear now to be the best candidates.

3.6 Fuels

Alternate fuels for vehicles have been subject to a great deal of study, particularly since the increased prices and predicted shortages of liquid petroleum fuels. One conclusion that appears clearly from this work is that liquid petroleum has unique advantages as a fuel for military vehicles. On a weight and volume basis alone, its advantages are clear, but when other military requirements are added, the advantages become overwhelming.

For long-range vehicles that are severely weight-limited, a possible alternate fuel is liquid hydrogen (LH_2). This results from the fact that LH_2 has roughly three times the energy content per pound of liquid petroleums. It also occupies about four times the volume of liquid petroleum for the same energy content, and thus LH_2

can only be substituted for liquid petroleum in situations where large volume changes do not proportionately degrade vehicle performance, i.e., in weight-limited vehicles (see Table 2-5). If the vehicle is severely weight-limited, LH_2 may increase its range capabilities. Examples of this situation are subsonic transport aircraft and some types of high-speed ships. When the factors of cost and logistic supply are considered, however, these possibilities become last resort solutions for military vehicles.

One military need that the potential petroleum shortage has pointed up is the desirability of multifuel capability. The Army has always had multifuel capability as a goal in order to optimize war-time logistic problems, but the Navy has not had the same pressure. Under the current petroleum supply situation, it appears that multi-fuel capability should become a priority goal for Technology Base activities.

4. TECHNOLOGY BASE PROGRAMS

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4. TECHNOLOGY BASE PROGRAMS

In this section, the current and projected Technology Base propulsion system programs for surface vehicles are reviewed. Input information for this task is taken from available survey and planning documents. For land vehicles, these documents include the Land-Mobility TCP mentioned in the Task Order (Section 1), the TACOM 20-year Plan for Propulsion Systems for Combat Vehicles, and the AMC Long-Range Fuels R&D Program. For sea vehicles, the pertinent documents are the Ocean Vehicles TCP referred to in the Task Order (Section 1) and the Survey of the Navy's Nonnuclear Propulsion Systems Development Programs. Comments on the Navy Nuclear Propulsion Program are also made but are not based on any single survey or planning document.

Considerable effort was made to verify the information contained in these documents by an independent survey of the pertinent R&D programs described in the DDC Data Base. Because of the diversity of the subject matter involved, this job became very time-consuming and was finally abandoned. Visits were made to both Army and Navy R&D centers involved in propulsion system work and to several contractors in order to obtain independent information on the nature and scope of the R&D work currently under way. The documents cited above, however, are the best sources of comprehensive information that were found.

4.1 Land Vehicles

4.1.1 The Land-Mobility TCP

It is pointed out in the Land-Mobility TCP that because of the enormous diversity of technology relative to land mobility and the lack of a comprehensive methodology to quantify results, many supporting analyses are more qualitative than quantitative. The scope of the survey covers all types of Army land vehicles--combat, transport, and special-purpose. It involves evaluation of the effects of evolving mobility doctrine and threat, as well as the impact of potential petroleum fuel supply problems. It also considers interfaces with

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other technology areas such as materials, weapons, structures, electronic devices, etc.

Only a small part of this total scope is directly concerned with advanced propulsion systems. As pointed out in Section 2.0, advanced propulsion is primarily for high-performance vehicles as defined there, which corresponds to the classes of high and standard mobility used in the TCP. In terms of technology subareas, the Technology Base program defined by the TCP is shown in Table 4-1 where those items that can be directly related to the subject matter of this survey are outlined in boxes. There are, of course, other areas such as reduction of vehicle signatures, improved RAM-D,* pollution abatement, etc., which relate to propulsion systems. It is not possible, therefore, from this breakout to give a total dollar figure on the amount being invested in advanced propulsion programs. For our purposes, the directly identified items on power plant, transmission, suspension, fuels, and controls will be adequate.

The TCP does not examine in detail the work being done in each of these subareas. Instead, it sets out a list of priority objectives by identifying the major functional needs of the various elemental land-mobility systems, and relating them to specific technology tasks. The results of this analysis are summarized in Table 4-2. As is pointed out in the TCP, the technology program for FY 73 and FY 74 did not adequately support these priorities. A major recommendation was to realign the program and provide additional funding, where needed, to remove this deficiency. An examination of the FY 75 program as part of this survey shows that the recommendation is, in fact, being implemented.

4.1.2 The TACOM 20-Year Plan for Propulsion Systems for Ground Combat Vehicles

The basic objective of this plan is to establish a technology development program for propulsion systems for combat vehicles without waiting for a specific vehicle application. The goal is to have

*Reliability, Availability, Maintainability-Durability.

TABLE 4-1. PROGRAM COMPOSITION BY TECHNOLOGY SUBAREAS

SUBAREA	FY73 K$	FY73 % of Total	FY74 K$	FY74 % of Total
TOTAL SYSTEMS	934	4.5	1575	6.9
Vehicle concept studies	422	2.1	460	2.0
Development, interfacing of analytical & experimental methodology	207	1.0	315	1.4
Reduction of vehicle signatures	100	0.5	600	2.6
Sea to inland logistic system	205	1.0	200	0.9
ELEMENTAL SYSTEMS	13278	64.5	12889	56.4
Experimental vehicles (combat, tactical and special purpose)	1431	7.0	819	3.6
Methodology development & validation	939	4.6	900	3.9
Basic supporting research	590	2.9	650	2.8
Material handling equipment (including POL handling)	1353	6.6	1872	8.2
Gap crossing vehicles & equipment	295	1.4	555	2.4
Auto fuels, lubes & chemicals	1500	7.3	1798	7.9
Countermine R&D	6660	32.4	5290	23.2
Earth moving, excavating, road surfacing equipment	410	2.0	905	4.0
Maintenance equipment	100	0.5	100	0.4
SUBSYSTEMS	6363	30.9	8377	36.7
Power plant	1960	9.5	3090	13.5
Transmission & line of drive	320	1.6	520	2.3
Suspension & running gear	1730	8.4	2110	9.2
Controls & diagnostics	500	2.4	450	2.0
Improved RAM-D	335	1.6	470	2.1
Pollution abatement	1230	6.0	1000	4.4
Development, interfacing of computerized experimental methodology	68	0.3	557	2.4
Improved environmental resistance	220	1.1	180	0.8
TOTAL	20575		22841	

available from Technology Base programs, demonstration models of propulsion system components (engines, transmissions, and ancillary equipment) for direct use in Technology Applications (6.4 programs). The family concept is favored as a means of reducing R&D costs.

Technology goals are set to meet two major requirements--forecasted fuel posture and forecasted vehicle requirements. Work under 6.2 program funds is to include the following:

- Advanced diesel technology, including variable geometry turbochargers, turbocompounding, and universal fuel injectors.
- Advanced turbine technology, including new cycles, higher temperature materials, reduced cost, greater dust tolerance, greater fuel tolerance, and fuel economy.
- Expanded stratified charge engine technology to V8 engines up to 1000 hp.
- Technology for external combustion engines such as Rankine and Stirling cycle.
- Study of engines compatible with atomic power plants and mobile energy depots, including electric-powered vehicles.
- Advanced power train technology to include variable-pitch torque converters, electronic and fluidic logic circuitry, and power trains compatible with vapor-cycle engines.
- Improved air filtration technology and advanced heat exchangers.
- System integration technology for optimum power train matching.

Funds in the 6.3 area are to be used to develop "demonstrator" prototypes of engines and transmissions based on improved technology from the 6.2 programs.

The overall program would investigate engines of the size and type shown in Table 4-3 for potential use in the time periods indicated. The funding requirements are projected as shown in Fig. 4.1.

The general comment that can be made immediately about this plan is that it is too diffuse. The funding requirements are not enough to do everything that is envisioned. The program would be improved by greater focus, i.e., by eliminating many of the engine candidates.

(I) Elemental System	(II) Influence Factors: Cost of Defense	Fuel Crisis	Army of Future	Threat	Mobility Doctrine	Technology Complexity	Outside Technology	(III) Functional Needs/Opportunities	(IV) Pacing Technological Tasks/Problem
COMBAT VEHICLES									Improve RAM-D multi-fuel 1500+ HP turbine power
									Improve RAM-O of track and drive system
	0	0	0				0	RAM-D Improvements	Develop in-arm suspension system
									Improve RAM-D of auxilliary systems
									Develop advanced electric drive system
									Reduce tire vulnerability
	0		0	0	0	0	0	Mobility/Agility Improvements	Improve river-crossing performance
									Improve driver selection, skills
									Develop high output, low-lag transmission system
	0		0	C		0	0	Reduced Vulnerability	Integrate, optimize high mobility, high protecti
									Develop lightweight armor
									Reduce vehicle signatures
									Develop on-vehicle countermine measures
	0		0			0	0	Remotely Controlled Vehicle Development	Develop, integrate practical vehicle systems
									Define future fuel trends
		0						Power Plants for Future Fuels	Develop fuel tolerant military engines
TRANSPORT VEHICLES	0				0	0	0	Inventory Reductior	Develop optimum high-mobility designs
	0						0	Load-Carrying Improvements	Improve materials, structures
									Improve RAM-O of auxilliary systems
	0		0			0	0	RAM-O Improvements	Develop advanced electric-drive systems
									Develop high-performance suspensinns
									Optimize design, performance of tires
									Improve river-crossing performance
	0		0	0	0	0	0	High-Mobility Improvement	Improve soft-soil, snow performance and slippery
									Develoo oositive individual wheel drive
									Improve driver selection, skills
	0			0		0	0	ACV Exploitation	Define, optimize ACV role in military land mobili
SPECIAL PURPOSE VEHICLES AND EQUIPMENT			0	0			0	Individual Soldier Mobility	Develop small, high-performance thrusters
	0						0	Maintenance Improvements	Improve maintenance equipment
	0			0	0	0		Inventory Reduction	Integrate, optimize system morphology, design
				0		0		Mobility Improvements Under Special Adverse Conditions	Develop hybrid suspension vehicles
	0		0			0	0	Remotely Controlled Vehicle Development	Develop, integrate practical vehicle systems
MATERIALS HANDLING EQUIPMENT	0						0	Cargo Protection Increase	Improve container structures, materials
	0				0	0	0	Intermodal Materials Handling Improvements	Define, optimize role of advanced man-amplifiers
									Develop/adapt air-cushion support devices
	0			0	0		0	Container Handling Over Beaches in Forward Areas	Develop container-handling systems for beaches, u
									Design, evaluate vehicles for container transport
	0	0		0	0			POL Handling Improvement in TO	Develop, evaluate integrated forward area POL syst
	0						0	Control/Identification Improvement	Develop computerized field systems
ENGINEER CONSTRUCTION VEHICLES, EQUIPMENT	0						0	Improve Control, Flexibility	Develop advanced electric-drive system
GAP-CROSSING EQUIPMENT				0	0	0		Span Capability Increase	Systematic development of quantitative needs
									Improve structures, materials
	0				0	0		Transportability Improvement	Reduce weight, complexity
			0		0		0	Erection Time, Personnel Decrease	Develop automatic sequencing controls
AUTOMOTIVE FUELS AND CHEMICALS	0			0	0			Product Compatability, Military Needs	Define, develop requirements, tests
	0	0					0	Substitute Fuels	Develop synthetic fuel performance criteria
									Evaluate commercial developments in military conte
	0							Logistic Inventory Reduction	Develop performance criteria for multi-use fuels a
	0		0					Combat Fire Hazard Reduction	Develop fire-retardant/fireproof fuel
COUNTERBARRIER EQUIPMENT (includes countermine)									Innovate techniques, equipment for rapid reduction
				0			0	Counterbarrier Time, Loss Reduction	Systems engineering, design
	0						0	Logistics Burden Reduction	Improve barrier destruct weapons
									Improve soil stabilization, rapid excavation techn
									Develop explosive detector
				0	0		0	Countermine Effectiveness Improvement	Develop vehicle-mounted, nonweapons mine neutraliz
									Develop man-portable, nonweapons mine neutralizers
EXPEDIENT ENVIRONMENT MODIFICATION				C	0		0	Excavation Rate Increase	Develop high-speed, transportable excavation equip
	0						0	Logistics Burden Reduction	Develop new quarrying, crushing techniques, equipm
									Develop new expedient surfacing techniques, materi
	0			0	0	0	0	TO Trail/Road Preparation Time reduction	Develop improved dust palliatives

0 - Strong Influence

Priority Tasks

TABLE 3-2 summarizes major FUNCTIONAL TECHNOLOGY NEEDS OF LAND MOBILITY SYSTEMS, and identifies related Influence Factors, Pacing Technological Needs and Tasks, and classifies the last. Example: reading from left to right, under ELEMENTAL SYSTEMS (Col. I), select "Combat Vehicles." Four FUNCTIONAL NEEDS or OPPORTUNITIES associated with combat vehicles are identified in Column III. From these, select "Mobility/Agility Improvements," strong INFLUENCE FACTORS are keyed by the "O's" in Column II; the flared lines to the right indicate six related PACING TECHNOLOGICAL TASKS or PROBLEMS, Column IV. Selecting one of these, "Improve river-crossing performance," the "●" in the matrix to the right (Col. Vb) indicates the primary ASSOCIATED LAND MOBILITY TECHNOLOGY AREA, the "X's" in Column Vc denote secondary associations. (A "●" or "X" in Column VI would have indicated that the pacing problem was primarily or secondarily associated with IMPORTANT RELATED TECHNOLOGY AREAS outside of Land Mobility Technology.)

A

TABLE 4-2. LAND-MOBILITY PRIORITY PROGRAMS

(II) Influence Factors: Army of Future	Threat	Mobility Doctrine	Technology Complexity	Outside Technology	(III) Functional Needs/Opportunities	(IV) Pacing Technological Tasks/Problems	(V) (a) Total Systems Analysis	(b) Elemental Systems: Analysis, Design	System Integration	Prototype Development and Evaluation	(c) Subsystems Research Development, and Evaluation: Power Plant	Transmission and Line of Drive	Suspension and Running Gear	Controls	Auxiliary Systems	(VI) Important Related Technology Areas: Structures (TCP)	Materials (TCP)	Weapons (TCP)	Electronics TCP)	Roads/Highways (No TCP)
						Improve RAM-O multi-fuel 1500+ HP turbine power plant					●									
						Improve RAM-O of track and drive system							●							
0				0	RAM-O Improvements	Develop in-arm suspension system							●							
						Improve RAM-O of auxiliary systems									●					
						Develop advanced electric drive system						●							X	
						Reduce tire vulnerability							●				X			
0	0	0	0	0	Mobility/Agility Improvements	Improve river-crossing performance		●					X	X						
						Improve driver selection, skills		X						●					X	
						Develop high output, low-lag transmission system						●								
0	0		0	0	Reduced Vulnerability	Integrate, optimize high mobility, high protection designs	X	●	X	X										
						Develop lightweight armor		X								X	●			
						Reduce vehicle signatures		●			X	X	X						X	
						Develop on-vehicle countermine measures		●										X		
0			0	0	Remotely Controlled Vehicle Development	Develop, integrate practical vehicle systems	●	X	X										X	
					Power Plants for Future Fuels	Define future fuel trends	●													
						Develop fuel tolerant military engines					●									
		0	0	0	Inventory Reduction	Develop optimum high-mobility designs	●	X	X	X										X
				0	Load-Carrying Improvements	Improve materials, structures		●								X	X			
						Improve RAM-O of auxiliary systems									●					
0			0	0	RAM-O Improvements	Develop advanced electric-drive systems						●							X	
						Develop high-performance suspensions						X	●							
						Optimize design, performance of tires						X	●							X
						Improve river-crossing performance		●					X	X						
0	0	0	0	0	High-Mobility Improvement	Improve soft-soil, snow performance and slippery surface traction		X					●							
						Develop positive individual wheel drive						●								
						Improve driver selection, skills								●					X	
	0		0	0	ACV Exploitation	Define, optimize ACV role in military land mobility	●	X												
0	0			0	Individual Soldier Mobility	Develop small, high-performance thrusters						●								
				0	Maintenance Improvements	Improve maintenance equipment		●	X	X									X	
	0	0	0		Inventory Reduction	Integrate, optimize system morphology, design	X	●												
	0		0		Mobility Improvements Under Special Adverse Conditions	Develop hybrid suspension vehicles		●	X	X			X							
0			0	0	Remotely Controlled Vehicle Development	Develop, integrate practical vehicle systems	●	X	X										X	
				0	Cargo Protection Increase	Improve container structures, materials		●								X	X			
		0	0	0	Intermodal Materials Handling Improvements	Define, optimize role of advanced man-amplifiers	●	X												
						Develop/adapt air-cushion support devices	X	X	●	X										
	0	0		0	Container Handling Over Beaches in Forward Areas	Develop container-handling systems for beaches, unprepared sites	●	X	X	X										
						Design, evaluate vehicles for container transportation off road	X	●												
	0	0			POL Handling Improvement in TO	Develop, evaluate integrated forward area POL systems	X	X	●	X										
				0	Control/Identification Improvement	Develop computerized field systems		●											X	
				0	Improve Control, Flexibility	Develop advanced electric-drive system						●							X	X
	0	0	0		Span Capability Increase	Systematic development of quantitative needs	●													
		0	0		Transportability Improvement	Improve structures, materials		●								X	X			
						Reduce weight, complexity		●								X	X			
0		0		0	Erection Time, Personnel Decrease	Develop automatic sequencing controls		●						X						
	0	0			Product Compatability, Military Needs	Define, develop requirements, tests		●			X	X	X	X			X			
				0	Substitute Fuels	Develop synthetic fuel performance criteria		●			X									
						Evaluate commercial developments in military context		●			X									
					Logistic Inventory Reduction	Develop performance criteria for multi-use fuels and lubricants		●			X									
0					Combat Fire Hazard Reduction	Develop fire-retardant/fireproof fuel		●			X									
						Innovate techniques, equipment for rapid reduction of barriers		●												
	0			0	Counterbarrier Time, Loss Reduction	Systems engineering, design	●	X												
				0	Logistics Burden Reduction	Improve barrier destruct weapons		X										●		
						Improve soil stabilization, rapid excavation techniques		●												
						Develop explosive detector		●										X		
	0	0		0	Countermine Effectiveness Improvement	Develop vehicle-mounted, nonweapons mine neutralizers		●										X		
						Develop man-portable, nonweapons mine neutralizers		●										X		
	0	0		0	Excavation Rate Increase	Develop high-speed, transportable excavation equipment		●	X											X
				0	Logistics Burden Reduction	Develop new quarrying, crushing techniques, equipment	X	●	X											X
						Develop new expedient surfacing techniques, materials	X	●	X											X
	0	0	0	0	TO Trail/Road Preparation Time reduction	Develop improved dust palliatives		●												

0 - Strong Influence

Priority Tasks

●	Primary Association
X	Secondary Association

The rationale for doing this is given in Sections 2 and 3 of this report. Even when the goals are trimmed down, the R&D funds foreseen for engine technology development do not appear excessive when compared, for example, to the Technology Base funding which supports aircraft and helicopter gas-turbine developments.

TABLE 4-3. FUTURE ENGINE CANDIDATES

Vehicle Weight Class	Horsepower Range	Candidate Engines for Time Period		
		Short (1975-80)	Mid (1980-85)	Long (1985-95)
Heavy (40-60 Tons)	750-2000	Diesel Turbine	Turbine (Advanced) Diesel (Turbocompound)	Turbine Diesel Stratified Charge External Combustion
Medium (20-40 Tons)	400-1500	Diesel Turbine	Diesel Turbine Stratified Charge External Combustion (Stirling)	Turbine Diesel Stratified Charge External Combustion
Light (10-20 Tons)	200-750	Diesel Stratified Charge	Stratified Charge Turbine Diesel	Turbine Diesel Stratified Charge External Combustion

4.1.3 The AMC Long-Range Fuels R&D Program

The objectives of this document are (1) to provide guidance for Army power plant R&D and (2) to define a revised Army Fuels R&D Program. With respect to power plant R&D, the following guidelines are presented:

- Conventional crude-based fuels will be available into the 1990s. By 1985, "conventional" fuels from other sources (shale, coal) will be in use.
- Unconventional fuels may be required in combat situations from now on. The nature and order of preference for use of unconventional fuels are shown in Table 4-4.
- Future fuels for beyond the 1990s into the 21st Century will include liquid hydrocarbons, hydrogen, and high-energy formulations.

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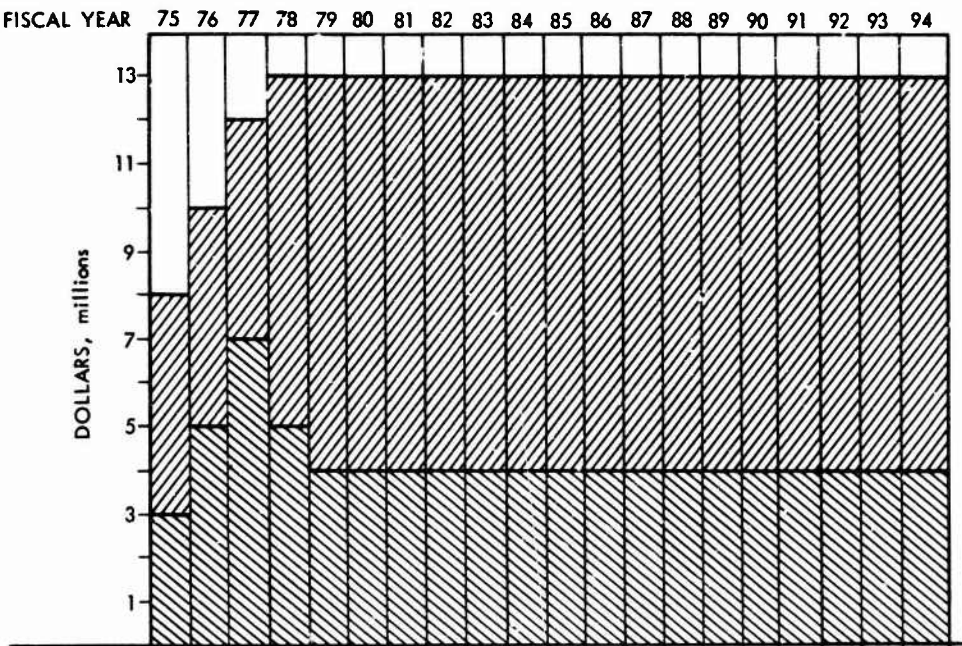

FISCAL YEAR	75	76	77	78	79	80	81	82	83	84	85	86	87	88	89	90	91	92	93	94	TOTAL
6.2	3	5	7	5	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	86
6.3	5	5	5	8	9	9	9	9	9	9	9	9	9	9	9	9	9	9	9	9	165
TOTAL	8	10	12	13	13	13	13	13	13	13	13	13	13	13	13	13	13	13	13	13	251

6.2 EXPENDITURE 6.3 EXPENDITURE

CONSTANT 1974 DOLLARS

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FIGURE 4.1. 20-Year Plan RDT&E Funding Summary

TABLE 4-4. PREFERRED USE OF UNCONVENTIONAL FUELS IN VEHICLES

	Type of Engine		
Type of Fuel	Diesel	Turbine	Spark Ignition
Residuals	√	√	
Crudes	√	few	few
Distillates	√	√	some
Jet Kerosene	√	√	
Plant Condensates		√	√
Jet Naptha	few	√	
Alcohols, ammonia, LPG, natural gas	not recommended at present		

On this basis, it is recommended that emphasis on power plant R&D be on the use of conventional and synthesized hydrocarbon fuels with secondary emphasis on hydrogen.

With regard to the second objective, the Army Fuels R&D Program is revised to place more emphasis on availability than on performance. In conventional fuels the objective is to continue ensurance of excellent performance and minimum cost when fuels are available but to add the options of using off-spec fuels when that may be necessary. In emergency fuels, i.e., existing products that can be made quickly available, R&D will be done to identify and adapt these fuels for Army use. For the long-term future, other fuels need to be considered and R&D will be done on use of synthetic hydrocarbons and hydrogen. The funding needed to support this program is shown in Fig. 4.2.

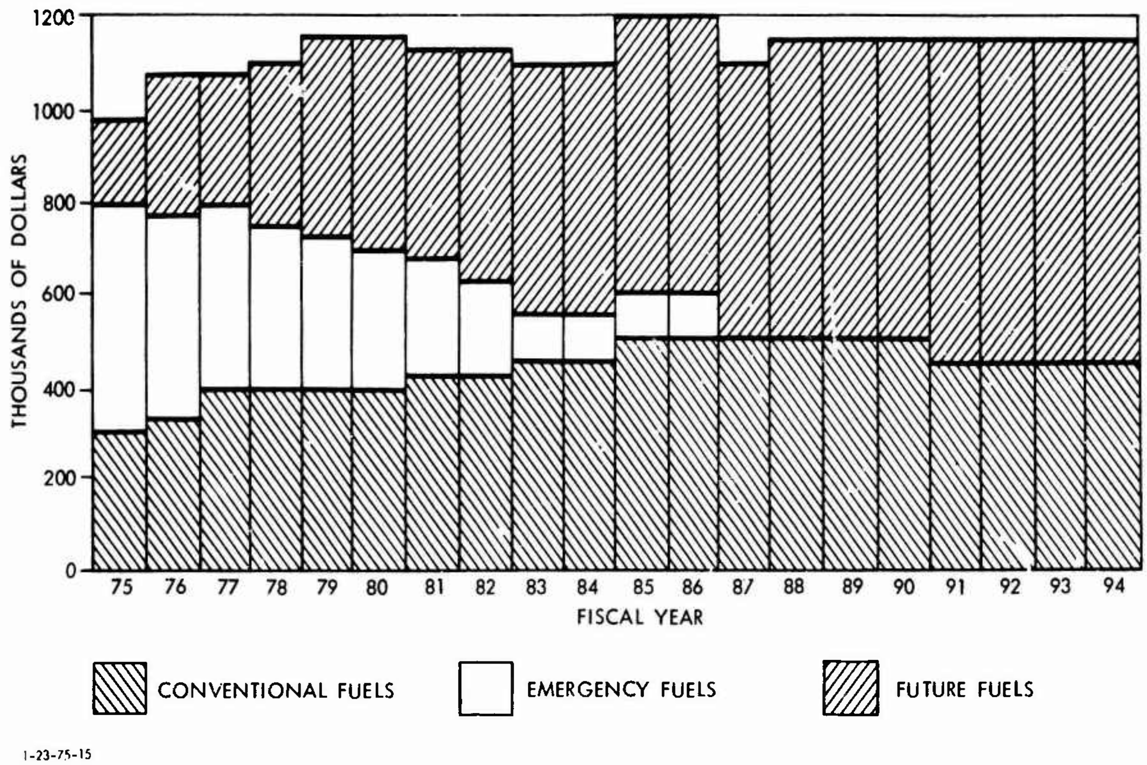

FIGURE 4.2. 20-Year Plan R&D Funding Summary

A general observation on this proposed program is that, while the nature of the problem is identified correctly, the time scale is probably too short. If the time scale is extended by a factor of two, which seems reasonable in the light of recent studies, the immediate guidance for propulsion system technology is to seek multi-fuel capability within the conventional fuels.

4.2 Sea Vehicles

4.2.1 The TCP on Ocean Vehicles

In the Introduction to the TCP, it is pointed out that to meet its basic mission requirements, the Navy needs a strong R&D program in ocean vehicle technology with particular attention given to the problems of:

- Obsolescence
- Increased threat
- Decreased funding and increased costs.

The purposes of the TCP are to relate investment in the 6.1, 6.2, and 6.3 program areas to projected needs, to identify pacing problems and unfunded areas, and to recommend priorities. It considers ocean-going and inshore vehicles as platforms which include:

- Hull
- Superstructure
- Propulsion
- Electric power
- Ship control
- Ship silencing
- Interior communications
- Auxiliary machinery
- Anti-pollution efforts
- Reduced manning
- Computer-aided design and construction.

The military systems carried by the platforms are not considered, nor are oceangoing barges and platforms and nuclear propulsion systems.

The basic breakdown of the R&D work in the 6.2 and 6.3 areas is in terms of the type of ship whose development it is supporting. The following ten ship categories are selected:

- Conventional Surface Ships
- Advanced Hydrofoils
- Surface Effects Ships
- Air-Cushion Vehicles
- SWATH and Multihull Ships
- Crafts and Boats
- Submarines
- Submersibles and Swimmer-Delivery Vehicles
- Bottom Crawlers
- Towed and Tethered Vehicles

In the 6.1 area of basic research, no such breakdown is attempted; this area is presented in a separate section.

The military needs and R&D emphasis, as stated in the TCP are summarized in Table 4-5. The total funding for the 6-year period considered in Table 4-5 amounts to $1003.8 million and does not include 6.1 Research funds which amount to $29.8 million (3 percent).

A significant observation from Table 4-5 is that the development of unconventional, high-speed, oceangoing ships (i.e., hydrofoils, SESs, and multihull ships) has been allocated about two-thirds of the total 6-year effort. This implies a top priority need for high-performance oceangoing escorts, which should be substantiated much more strongly than is done in the TCP.

The immediate concentration of effort is to develop a 2000-ton SES with a speed range of 80 to 100 knots (p. 43 of the TCP). While the speed range has been modified since this was written, there is still major emphasis on this vessel and it is generally believed to be a prototype for larger operational SESs in the 1980s. A basic problem of high-speed ships is that, at the current state of the art in propulsion systems, their range is limited. In addition, because of their high-power requirements they are relatively expensive.

TABLE 4-5. SUMMARY OF OCEAN VEHICLES R&D PROGRAM

Problem	R&D Goal	R&D Projected Effort* (6 yrs - FY 73 to FY 78) Category	Dollars, Millions	Percent of Total Effort
	An overall R&D goal is to reduce costs for acquisition, operation, and maintenance of all ocean vehicles and to minimize manning requirements.			
For conventional ships, top speed is 30-40 knots in calm water and much less in heavy seas.	Demonstrate high-performance vehicles with greater speed in calm and rough seas that are smaller, more cost/mission effective, and less susceptible to attack.	Conventional Ships	92.7	9
		Hydrofoil Ships	138.2	14
		Surface Effects Ships	448.3	45
		Multihull Ships	45.8	5
Modern submarines are approaching underwater speeds equal to displacement ships, but they must run slowly to reduce noise. There is need for better control systems at high speed.	Improve speed, control, depth, quieting, and magnetic concealment of submarines.	Submarines	80.4	8
TRIESTE is the only submersible for depths over 12,000 feet. It is slow, carries a small payload and lacks maneuverability.	Develop equipment for ocean bottom search, rescue, salvage emplacement, construction, inspection transportation, clandestine operations, and neutralization of weapons and sensors.	Submersibles	47.9	6
		Towed and Tethered Vehicles	16.7	
		Bottom Crawlers	0	
Present landing craft are slow, limited by surf conditions, and must unload at water's edge. They are vulnerable to both accident and enemy action.	Demonstrate less vulnerable vehicle with better performance.	Air-Cushion Vehicles	94.9	9
Current high-speed planing craft are rough riding, even in moderate seas, and carry small payloads.	Demonstrate vehicles with better performance.	Crafts and Boats	38.9	4

*Includes 6.2 and 6.3 funds.

Cost and range limits are discussed in general in Section 2 and the implications of these problems for high-speed ships is discussed below.

4.2.2 The Nonnuclear Propulsion Systems R&D Program for Sea Vehicles

The basic purpose of this document is similar to the Army's 20-Year Engine Plan, that is, to provide a focused R&D program for propulsion systems that is independent of a specific vehicle development. This approach has not been Navy practice, but it is now needed to reduce the risks encountered in 6.4 program area developments. The program that is proposed is summarized as follows:

- Gas-Turbine-Propulsion Systems--Develop a family of standard propulsion system components for delivering up to 60,000 to 70,000 hp per shaft. Determine the feasibility of split turbines, alternative fuels, and high efficiency recuperative systems. Establish a land-based turbine test bed.
- Steam Plants--Develop automatic control systems.
- Transmissions--Develop a family of planetary-type reduction gears and right-angle drives for high-power systems. Develop a superconducting drive system with up to 30,000 to 40,000 hp.
- Propulsors--Develop water-jet propulsors for up to 60,000 hp and speeds of 50 to 100 knots. Develop design criteria for trans- and supercavitating propellors. Improve efficiency of propulsion/lift air fans.
- Control Automation--Explore possibility of "fully automated" ship operation. Develop diagnostic systems and a family of solid-state frequency converters (10 kW to 250 kW).
- Test Facilities--Construct a test and engineering ship for evaluation of main propulsion systems.

It is shown that current programs to "predevelop" propulsion systems for undefined future vehicles exist only in gas-turbine marinization and in superconducting transmissions. For FY 75, these two areas are funded at about $21.6 million. To implement the remainder of the suggested program would require an additional $20.4

million. These funds are for 6.3 programs and above, and are to include both Technology Base and Technology Applications areas.

4.2.3 Nuclear Propulsion Systems

The exact separation between Technology Base and Technology Applications activities was not made in this area. It appears, however, that possibly $7 million to $10 million is the annual funding for Technology Base activities. These have been successfully directed at increasing core life as well as improving reliability. The important observation in this area is that no serious effort has been directed to reducing specific weight and volume. The position that has been taken is that Navy demands for ruggedness and at-sea maintainability preclude the approaches that would appreciably reduce specific weight. With the excellent record of success in operating nuclear propulsion systems, these stringent criteria can scarcely be criticized. The implications of this "freeze on weight-reduction" are discussed in Section 5.

5. ISSUES AND FINDINGS

5. ISSUES AND FINDINGS

The primary purpose of this section is to assemble and compare the information presented in the previous sections on Needs (Section 2), Potential (Section 3), and Programs (Section 4), to illuminate the gaps and opportunities in propulsion Technology Base activities. The approach that is taken is to examine issues in selected areas so as to highlight specific problems.

Land and sea vehicles will be treated in separate subsections because there is little overlap in their demands on propulsion systems. The basic reasons for this are

- The vast difference in size between land and sea vehicles, which results in greatly different power level needs, i.e., 200-2000 hp for land vehicles and 6000-40,000 hp for sea vehicles.
- The much greater endurance required of sea vehicles than of land vehicles, which places much greater emphasis on reducing fuel load requirements in sea vehicles than in land vehicles.

Each of these differences has a major impact on the selection of feasible propulsion systems.

5.1 Land Vehicles

Issue: Dependence on Commercial Technology

Maximum installed power has increased from about 800 hp (M-60) to 1300-1500 hp (XM-1) and is projected to go as high as 2000 hp (Sections 2 and 4). This has a major impact on Technology Base activities, since in the 800- to 2000-hp range there is little commercially developed propulsion system technology that can be used. As long as the top power demand was 800 hp, all propulsion system components could be derived from technology developed for other uses. However, commercial propulsion technology in the 800- to 2000-hp range is largely for locomotives, ships, and large electric-drive mining trucks, none of which will meet the specific weight and volume limits imposed on military land vehicles.

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Finding: The push toward higher power is separating the Army from its traditional commercially supported Technology Base. Increasing emphasis and expenditures in DOD Technology Base activities will be needed to support this move. Current levels of funding (Section 4) seem inadequate when compared to aircraft propulsion R&D expenditures.

Issue: Engine Types

In engine types for high-performance vehicles, the Army has for many years been moving toward an all-diesel status. This was a sound policy, based on the fact that the technology for diesels up to 800 hp was at hand and the diesel satisfies military specifications. If requirements are raised to 2000 hp, however, the gas turbine appears as a strong competitor to the diesel because of the increasing problem the diesel has in meeting specific weight and volume limits as power increases above 800 hp (see Section 3 and Appendix G). In the XM-1 program, there is a diesel/turbine competition at 1300 to 1500 hp, which results from a stand-off in the assessment of relative capabilities at the initial design stage. Technology Base guidance on this issue will not be completely provided by the XM-1 decision, however. The question that needs answering is--will future mobility demands require even greater power than the XM-1, which favors gas turbines, or will the power trend level off or decrease, thus allowing retention of the all-diesel policy?

Finding: There is a critical need to define future land vehicle requirements in installed power more closely in order to formulate a rational Technology Base engine program. A major deficiency in the current program is that the already meager resources are split between supporting high-powered diesels and equivalently powered gas turbines. A decision to go one way or the other would help alleviate this problem. A corollary finding is that in the 200- to 2000-hp range Technology Base activities related to engines other than diesels or turbines are not needed.

Issue: Conventional vs. Electric Transmissions

Mobility demands on transmission systems have two major effects. One is the need for going to higher power systems, the other is the possible need for multipoint power distribution, e.g., for individual-wheel-drive, articulated vehicles.

The need for higher power systems of standard type (mechanical, hydromechanical, hydrokinetic) can be met from existing technology. Considerable development work is needed to adapt to a specific need, but there is no apparent demand for new technological advances. The possible need for multipoint power distribution tends to favor electric transmission systems and needs more consideration.

> Finding: In FY 75 the Army has dropped all electric transmission projects after a steadily decreasing yearly allocation for many years. There is a need to continue some Technology Base activity in this area, at least to monitor the rapidly changing technology in solid-state devices (see Section 3) and as long as articulated, wheeled vehicles are of possible interest.

Issue: Wheel vs. Track as High-Mobility Thrusters

The wheel and the track are the established thrust devices for all current land vehicles. The possibilities of other kinds of thrusters have continually excited the imagination of inventors, and an impressive variety of devices have been designed and tested. The demand for greater mobility tends to fuel this activity but experience has shown that all except the wheel or track have limited usefulness.

It is common knowledge that the all-axle drive greatly improves the tractive ability of wheeled vehicles. Further improvement can be gained by articulation and by individual wheel drive. What is pointed out in Appendix E, however, and is commonly overlooked, is that in common off-road conditions the wheel is no match for the track in tractive power capability. The track gets into trouble only where the soil loses its ability to absorb power, i.e., wet or cultivated soil, but so do all thrusters, and those with less contact area become stalled earlier than the track. Under such conditions the soil is beginning to act as a liquid rather than a solid and a specialized type of thruster is needed.

Finding: The wheel and the track will continue to be the preferred thrusters for Army vehicles. However, there is an urgent need for more careful and exact terrain-operating specifications for off-road vehicles since it is these specifications and not vehicle design details which determine whether the track or wheel is to be used. As the specified terrain conditions become more severe the track becomes mandatory (see Appendix E). On the other hand, the articulated wheeled vehicle can provide greater agility and speed under less severe conditions. Correct specifications are thus of critical importance.

Issue: Definition of Mobility Limits

It is clear from the above discussion that it is important to determine the limits governing mobility. This is a task requiring combined modelling and experimentation. The Land-Mobility TCP recognizes the problem as a need to establish a methodology for computing mobility and gives it top priority. In response to this emphasis, improved terrain-vehicle interaction computer models, and improved computer-assisted vehicle design techniques are being established. These programs do not exactly answer the questions posed above, however.

Finding: Mobility modelling and analysis are not providing adequate data on mobility limits, and such data are needed to guide Technology Base activities. A combined experimental-analysis program with the following goals is apparently needed:

- Determine if agility rather than speed is the power-determining factor (as suggested in Appendix E).
- Find what levels of agility/speed give attractive pay-offs in reduced vulnerability (i.e., quantify the type of study done in the HELAST project).

- Determine agility/speed effects on offensive capabilities and needs.
- Assess, for practical scenarios, what terrain limitations there are on the use of power (extension of Appendix E).

This program would require building and testing purely experimental vehicles in order to extend and validate the mobility and design models. The results could then be used to establish specific power and thruster specifications for evaluating conceptual vehicle designs and for guidance of Technology Base programs.

Issue: The Family Concept for Components

A recurrent theme in Army R&D is the advisability of establishing families of components so that new vehicle requirements can be met with off-the-shelf components. From a cost-saving viewpoint, this is, on the surface, an attractive proposition. However, in the history of predeveloped hardware, many examples can be found where this policy did not work. When the time comes to build a new vehicle, there are frequently some special requirements that make the decision to design a new component more attractive than to use an existing device. Counter examples can also be found, though generally in small items.

Finding: There is need to study the conditions under which the family concept in engines, transmissions, and running gear would be useful. Certainly it would seem necessary to have the results of the mobility study suggested above before reasonable family ranges could be determined. Other factors would be the projected total demand for each family member and an assessment of the risk of obsolescence through application of new technology at a later date.

5.2 Sea Vehicles

Issue: Emphasis on High-Speed Ships

As with land vehicles, the primary motivation for improved propulsion systems for sea vehicles arises from demands for better mobility. Unlike land vehicles, however, the result is not a demand for increased size but rather for reduced weight. Propulsion systems of a few pounds per horsepower and installed power of 100,000 to 150,000 hp are needed for high-speed (>50 knots) oceangoing escorts (Section 2). The marinized second-generation aircraft gas turbine has easily met this need in engines. Equivalent needs in transmission and thrusters are recognized in Technology Base activities and will be discussed below. The general observation to be made is:

> Finding: The demand for high-speed oceangoing ships could not be met until recently because propulsion systems were too heavy (Section 3, and Appendix F). The marinized second-generation aircraft gas turbines (e.g., the LM 2500) has changed this picture in recent years. Since then, virtually all nonnuclear Technology Base activities in propulsion systems for sea vehicles have become directed at high-speed ships (Section 4).

Issue: Development of a Family of Marinized Gas Turbine Engines

A gas turbine development program has been initiated by the Navy to meet future demands for lightweight propulsion systems. This is an ambitious program that proposes a family of engines and elaborate test facilities. The engines are to be aircraft derivatives. It should be observed that the Navy demand for gas turbine engines is relatively small. A small, high-speed escort like the SES 2000 has about the same installed power requirement as a large aircraft, e.g., the C-5. However, it would be procured in fewer numbers and at a slower rate than aircraft. A current example is the gas-turbine-powered DD 963 which uses four LM 2500 gas turbines. If the full quantity of 30 new ships are procured over the next several years, the total engine order will be 120 engines plus spares--a low number by aircraft standards.

Finding: In view of the low demand situation for marine gas turbines, a careful study should be made of the cost-effectiveness of predeveloping a family of engines. A corollary finding is that there is no perceived need for gas turbines over 40,000 hp (see Section 2, Size Limits).

Issue: Nuclear Propulsion as a Solution to the Range Problem

The second mobility demand is for range. For fleet submarines and large ships, nuclear propulsion systems have satisfied that demand, permitting indefinitely long operations at peak power output and improved logistic independence. Unfortunately, at the current state of technology (over 100 lbs/hp) they are too heavy for escort missions requiring speeds of over 30 knots (Section 2).

The thrust of nuclear propulsion technology improvements has been toward longer core life with greater reliability and maintainability as continuing goals. There is no directed effort being made to reduce specific weight (Section 4). The reason for this inaction is a position that the proposed lighter systems will not meet reliability and maintainability standards.

Finding: A reduction in weight by a factor of two would make nuclear propulsion clearly superior to gas turbines for escorts of DD 963 type. A reduction of weight by a factor of 8 to 10 would make nuclear propulsion feasible for high-speed ships of the SES 2000 type. Such weight reductions are technically feasible and undoubtedly will appear in time in commercial use (Appendix G). A directed Technology Base program could reduce the time to reach lightweight nuclear propulsion systems by a big factor.

Issue: High-power Lightweight Transmission Systems

The push to lighter weight propulsion systems requires reduced transmission weights also. Traditionally, the Navy has used large, low-speed shafts and gearing on surface ships. This was consistent with the large specific weights of conventional steam turbine plants.

High-speed ships require both a weight reduction of about a factor of 5 and angled drives since it is generally not possible to maintain an in-line thruster-engine geometry. This geometrical problem has led to a Technology Base program to develop superconducting electrical transmission systems for power levels up to 40,000 hp.

Finding: In general, lightweight transmission systems for high-speed ships require higher rotational speeds, more gearing, and different types of gears than have been used traditionally in the Navy. This technology is available at 4000 hp in helicopters and has been extended to 25,000 hp in design studies (for example, in the SES 2000 designs). Technology Base attention should be directed to applying this technology at the power levels required for Navy applications (up to 40,000 hp).

In pursuing the development of superconducting transmissions, the trade-off between ac and dc systems at the high-power levels required should be examined more carefully. It is possible dc systems may become too heavy as power level is scaled up.

Issue: High-Speed Thrusters

High-speed ships place difficult demands on thrust devices. To be effective, the conventional propellor must be driven into the cavitating regime, but this causes erosion problems and reduced efficiency. As a result, a wide variety of other thrusters have been investigated. These range from pure water-jets through air/water mixtures to pure air propellors. Air is difficult to use because of the need for a very large, low-speed propellor to achieve reasonable propulsive efficiencies. Air/water mixtures are better, but the pure water-jet seems to be the most practical of these devices.

Finding: High-speed ships need supercavitating propellors or water-jet thrusters. Both these devices are receiving adequate attention in Technology Base activities (Section 4). The relatively low efficiency of water-jets (~50 percent) is important because gas-turbine-powered high-speed ships are range-limited

(Section 2, and Appendix C). In the future, lightweight nuclear power could make this deficiency less important.

Issue: Military Usefulness of Petroleum-Fueled High-Speed Escorts

As noted several times above, the major thrust of Technology Base programs is to support the development of gas-turbine-powered high-speed ships. Gas turbines are undoubtedly an advance over conventional steam turbines for escort vessels up to 35 to 40 knots. At speeds over 50 knots, however, regardless of design, the power requirements are such that endurance is limited (Section 2). To achieve "oceangoing" range, a petroleum-fueled high-speed ship needs a low-power cruise mode. Unfortunately, all high-speed ship designs have greatly increased cruise-speed power requirements when compared to a displacement ship. The trend in high-speed ship design has been toward the high length/beam ratio SES in a successful effort to improve cruise power requirements, even at the expense of high-speed power needs (Appendix D). Even so, these ships will have less range than conventional escorts.

Finding: High-speed petroleum-fueled escorts will require frequent refueling. The effect of this limitation on possible missions should be evaluated, but it appears likely that ocean-going high-speed ships will not become practical Navy vessels until lightweight nuclear power is available in the indefinite future, or until hydrogen is accepted as an operational fuel. If so, then major changes in Technology Base emphasis are in order.

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APPENDIX A

TASK ORDER FOR WORK TO BE PERFORMED BY INSTITUTE FOR DEFENSE ANALYSES

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C O P Y

DEFENSE ADVANCED RESEARCH PROJECTS AGENCY
1400 Wilson Boulevard
Arlington, Virginia 22209

TASK ORDER FOR WORK TO BE PERFORMED
BY INSTITUTE FOR DEFENSE ANALYSES

TASK ORDER T-102 DATE 1 October 1973

ADVANCED PROPULSION SYSTEMS

You are hereby requested to undertake the following Task:

1. TITLE: Advanced Propulsion Systems.

2. TECHNICAL SCOPE: ADVANCED PROPULSION SYSTEMS. The purpose of this project is to conduct a survey of advanced propulsion systems for new types of land vehicles, ships and submarines. This survey will be used to provide inputs to the TCPs on surface vehicle technology and on topics relating to advanced propulsion and power systems. It will define the current state of-the-art, point out attractive opportunities and indicate gaps in the existing program. A srudy of the feasibility and military utility of light weight, wheeled air cushion vehicles will be completed. Propulsion and power systems analysis for small submarines will be completed.

3. SCHEDULE: The advanced propulsion systems technology survey and reports which provide input to the Surface Vehicle Technology Coordinating Paper are estimated to require one man-year of effort.

4. ODDR&E COGNIZANCE:
   a. Overall cognizance of this Task is within the Office of the Deputy Director, (Research and Advanced Technology), ODDR&E.
   b. Subtask assignments will come under the cognizance of the Assistant Director, (Engineering Technology).

5. SCALE OF EFFORT: One man-month per month average.

6. REPORT DISTRIBUTION AND CONTROL: All report distribution will be controlled by the office of technical cognizance.

7. SPECIFIC INSTRUCTIONS AND LIMITATIONS: None. Changes in scale of effort will not be made without the consent of DARPA.

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A "need-to-know" is hereby established in connection with this Task and access to information in the field of this Task is authorized for participating personnel and such supervisory and advisory personnel as deemed necessary. Department of Defense support, such as access to classified documents and publications, security clearances, and the like, necessary to complete this Task, will be obtained through the Director, DARPA.

/s/A.J. Tachmindji
for S.J. Lukasik
Director

ACCEPTED: /s/Alexander H. Flax
President, IDA

DATE: 1 October 1973

APPENDIX B

VEHICLE AND PROPULSION SYSTEM DATA

Data Sources:

Handbook of Army Material (Ref. C-3).

U.S. Army, Characteristic Data Sheets (Ref. C-5).

Jane's Fighting Ships 1974-1975 (Ref. C-4).

Diesel and Gas Turbine Catalog, Milwaukee, Wis., Diesel and Gas Turbine Progress, 1972.

Land Mobility Technology Co-ordinating Paper, 1 Nov. 1973.

Jane's Surface Skimmers: Hovercraft and Hydrofoils, New York, McGraw Hill, 1972.

E. Quandt "An Overview of High Performance Ship Propulsion Systems", a paper presented at the American Ordnance Association Meeting, NSRDC, Carderock, Maryland, 8 May 1973.

TABLE B-1. TRACKED ARMY VEHICLES

Designation	Weight (lbs)	Power (hp)	Specific Power (hp/ton)	Description
M 4	31,000	190	12	Tractor
M 8	45,000	500	22	Tractor
M 41	51,000	500	20	Tank
M 42	40,000	500	25	SP Gun
M 44	63,000	500	16	SP Gun
M 48	99,000	810	16	Tank
M 51	120,000	980	16	Recovery Vehicle
M 52	53,000	500	19	SP Gun
M 53	96,000	810	16	SP Gun
M 55	90,000	810	18	SP Gun
M 59	43,000	146	7	APC
M 60	101,000	750	15	Tank
M 67	105,000	810	15½	Tank
M 75	41,000	375	13½	APC
M 76	12,000	135	22½	Amphibian
M 84	47,000	146	6	Mortar
M 88	112,000	980	17½	Recovery Vehicle
M 106	25,000	215	17	SP Gun
M 107	62,000	405	13	SP Gun
M 108	40,000	405	18	SP Gun
M 109	52,000	405	15½	SP Gun
M 110	58,000	405	14	SP Gun
M 113	24,000	194	16	APC
M 114	15,000	160	21	APC
M 116	10,000	160	32	Cargo
M 125	24,000	194	17	Mortar Carrier
M 132	23,000	194	17	SP Gun
M 548	13,000	215	33	Carrier
M 551	34,000	300	18	SP Gun
M 571	8,000	86	21½	Articulated Carrier
M 577	23,000	194	17	Carrier
M 578	54,000	425	16	Recovery Vehicle

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TABLE B.2. WHEELED ARMY VEHICLES

Designation	Cross-Country Weight (lbs)	Power (hp)	Specific Power (hp/Ton)	Description
M 39	30,000	224	15.0	5-Ton Chassis, 6x6
M 44	18,000	146	16.2	2½-Ton Chassis, 6x6
M 123	59,000	300	10.2	10-Ton Tractor, 6x6
M 151A1	3,200	71	44.7	Jeep - ¼-Ton Truck, 4x4
M 520	40,800	213	10.4	Goer - 8-Ton Truck, 4x4
M 553	47,300	213	9.0	Goer - Wrecker
M 559	4,550	213	9.4	Goer - Tanker
M 561	10,200	98	19.2	Gama Goat - 1¼-Ton Truck, 6x6
M 656	27,000	200	13.5	5-Ton Truck, 8x8
M 715	8,900	133	30.0	1¼-Ton Truck, 4x4
M 746/7	193,000	600	6.5	Heavy Equipment Transporter

TABLE B-3. NAVY DISPLACEMENT SHIPS

Ship	Specific Power (hp/ton)	Length (ft) Water Line	Length (ft) Overall	Top Speed (knots)	Weight (Long Tons)	Power (hp)	Remarks
Destroyers							
DD 931	17.5		418	33	4,000	70,000	14 in Class
DDG 31	16.9		418	35	4,200	70,000	4 in Class
DDG 2	15.6		437	35	4,500	70,000	23 in Class
DDG 35	15.4		493	35	5,200	80,000	2 in Class
Escorts							
DLG 6	14.7		513	34	5,800	85,000	10 in Class
DLG 16	10.9		533	34	7,800	85,000	9 in Class
DLG 26	10.7		547	34	7,900	85,000	9 in Class
DD 963	10.0		560	33	8,000	80,000	Possible 30 in Class
DLGN 25	7.0	550	565	30	8,600	60,000	Nuclear
DLGN 35	6.5		564	30	9,200	60,000	Nuclear
DLGN 38	6.5		585	30	10,000	65,000	Nuclear
DLGN 36	6.4		596	30	10,200	65,000	Nuclear
Cruisers							
CG 10	6.9	664	673	33	17,500	120,000	3 in Class
CLG 3	6.9	600	610	32	14,600	100,000	6 in Class
CGN 9	4.6		721	30	17,400	80,000	Nuclear
Carriers							
CVA 41	3.3	900	979	33	64,000	212,000	3 in Class
CVA 59	3.0	990	1,039-47	35	78,000	280,000	4 in Class
CVA 63	2.9	990	1,047-72	35	80,800	280,000	3 in Class
CVAN 65	3.1	1,040	1,123	35	89,600	280,000	Nuclear
CVAN 68	2.9	1,040	1,092	35	91,400	280,000	Nuclear--Possible 3 in Class

TABLE B-4. HIGH-SPEED SHIPS

Designation	Power	Gross Weight	Sea State	Top Speed	hp/Ton	Remarks
Hydrofoils						
PCH-1	6,600	120	Calm	48	55	High Point Built
AGEH	28,000	320	Calm	87	87	Plainview Built
PGH-1	3,600	58	Calm	50	62	Flagstaff Built
PGH-2	3,200	58		50	55	Tucumcari Built
PHM	16,000	231		50	70	NATO Missile-Armed Patrol Boat
Surface Effect Ships						
Low L/B	135,000	2,200	0 3	85 68	60	Designed
High L/B	23,000	1,000	0 3	46 38	23	Estimates
	48,000	2,000	0 3	52 45	24	
	105,000	4,000	0 3	58 51	26	
	250,000	10,000	0 3	62 58	25	
Air-Cushion Vehicles						
7380 Voyageur	3,400	45.5	0	58	75	Built
7501 Viking	1,700	16	0	58	105	Built
SR-N3	3,900	41.5	0	81	93	Built
SR-N4	13,600	202	0	75	67	Built
BH.7 Wellington	3,400	57	0	75	60	Built
SES 100A	11,200	126	0	92	89	Built
SES 100B	13,500	105	0	92	128	Built
JEFFA	18,800	170	0	50	110	Designed
JEFFB	18,800	177	0	50	105	Designed

TABLE B-4. (Continued) HIGH-SPEED SHIPS

Designation	Power	Gross Weight	Sea State	Top Speed	hp/Ton	Remarks
Multihull Ships						
SWATH	65,000	2,370		39	27	Estimates
	60,000	3,000		34	20	
	62,000	5,550		29	11	
Planing Craft						
PG-84	16,900	225	0	45	75	Built
CPIC	6,000	75	0	45	80	Built
SSP	6,400	190	0	25	34	Designed

Page 2 of 2

TABLE B-5. OPERATING PROPULSION SYSTEMS--HIGH-SPEED SHIPS

A. U.S. NAVY HYDROFOILS

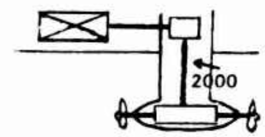
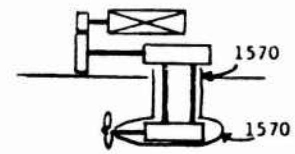
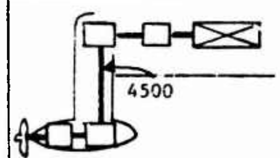
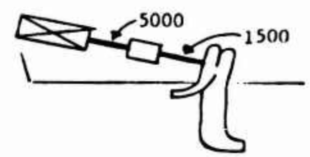
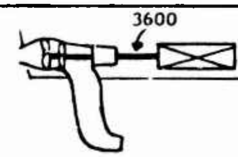
SHIP			ENGINE				PROPULSOR				
IDENTIFICATION	WEIGHT	SPEED	NUMBER	TYPE	MAX CONT POWER	RPM OUTPUT	NUMBER	TYPE	RPM	LOCATION	TRANSMISSION ARRANGEMENT
PCH-1	120	45	2	PROTEUS	3200	5000	4	Subcavitating	1500	Twin Aft Struts	
AG [illegible]	320	50	2	LM-1500	14,000	5500	2	Supercavitating 62" Diameter	1570	Twin Forward Struts	
PGH-1	58	50	1	TYNE	3600	13,000	1	45 in. Dia. Controllable Pitch	1050	Single Stern Strut	
PGH-2	58	50	1	PROTEUS	3200	5000	2	Centrifugal Pump	1500	Twin Aft Strut Inlets	
PHM	215	50	1	LM-2500	22,000	3600	1	Two Stage Axial Flow Pump	-	Twin Aft Strut Inlets	

TABLE B-5 (Continued)

B. U.S. NAVY AIR-CUSHION CRAFT

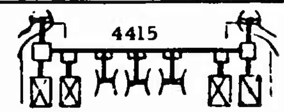
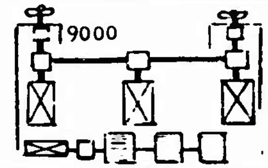
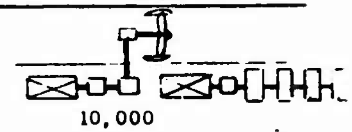
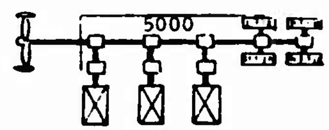
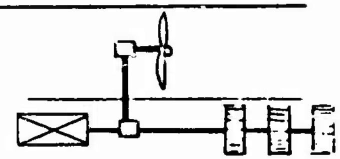
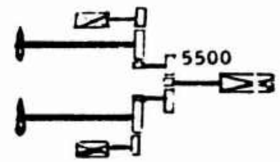
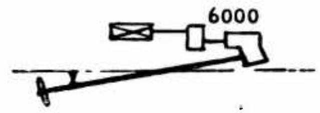
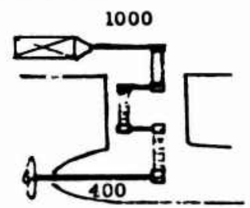
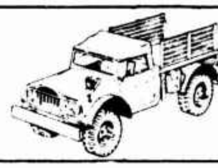
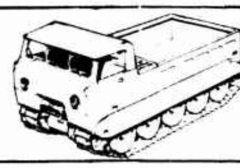
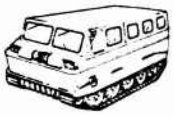
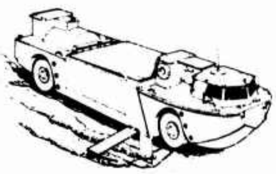
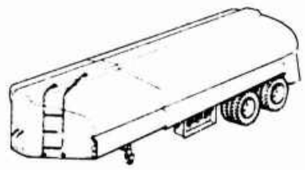
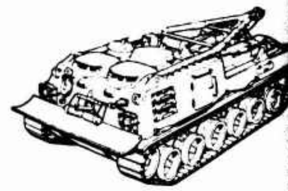
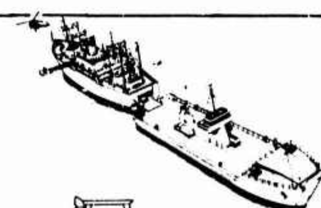
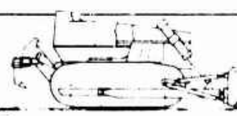
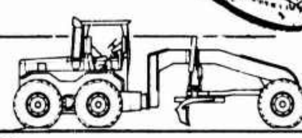
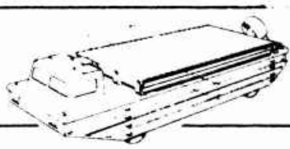
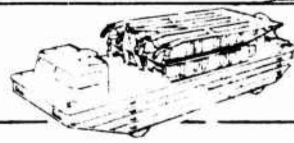
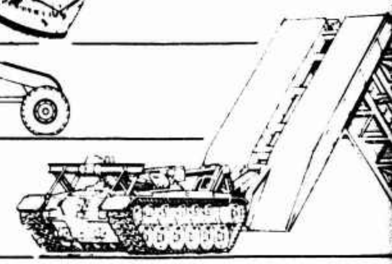
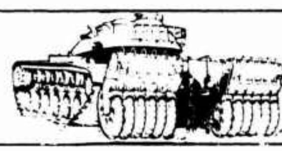
Ship			Engine				Propulsor/Lift				
Identification	Weight	Speed	Number	Type	Max. Cont. Power	RPM Output	Number	Type	RPM	Location	Transmission Arrangement
SES-100A	100	80	4	TF-35	2800	14,500	2	Waterjets 22" dia pump 6" dia nozzle	4200	Aft Sidewalls	
							3	Axial Fans	2680	Aft Deck	
SES-100B	100	80	3	FT-12	4500	9,000	2	Partially Submerged Propellers 3.5 ft. dia.	2613	Aft Sidewalls	
			3	ST-6	510	31,500	8	Centrifugal Fans	2100	Forward Deck	
JEFF-A	150	50	6	TF-40	3350	15,400	4	Fan Jets 8 ft. dia.	1800	At Craft Corners	
							8	Centrifugal Fans	2500	In Craft Sidewalls	
JEFF-B	150	50	6	TF-40	3350	15,400	2	Ducted Air Propellers 12 ft. dia.	1250	At Stern of Craft	
							4	Double Entry Centrifugal Fans	1900	In Craft Sidewalls	
ASEV-X	730	90	2	LM-2500	22,000	3,600	2	30 ft. dia. Air Propellers, CRP		Above Deckline	
							4	Centrifugal Lift Fans		In Craft Forward	

TABLE B-5 (Continued)

C. U.S. NAVY ADVANCED DISPLACEMENT/PLANING CRAFT

SHIP			ENGINE				PROPULSOR				Transmission Arrangement
Identification	Weight	Speed	Number	Type	Max. Cont. Power	RPM Output	Number	Type	RPM	Location	
PG-84	225	45	1	LM-1500	14,000	5500	2	CP Propellers	400	Conventional Shaft & Strut	
			2	Diesel	1,450	--					
CPIC	75	45	3	TF-25	2,000	14,000-	3	24 in. dia Newton Rader	2000	Conventional Shaft & Strut	
SSP	190	45	2	T-64	3,200	1000	2	6 ft. dia CRP Propellers	450	Aft End of Lower Hull	

Page 3 of 3

Elemental Systems	
Combat vehicles	   
Tactical (including transport) vehicles	  
Special purpose vehicles and equipment	   
Materials handling equipment	 
Engineer construction vehicles and equipment	 
Gap-crossing vehicles and equipment	  
Automotive chemicals	
Counterbarrier equipment (including countermine)	
Expedient environment modification	

*Mission includes logistical support. Vehicles may be either tracked or wheeled, with varying levels of cross-country mobility, water-crossing capability and environmental tolerance.

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TABLE B-6. ARMY VEHICLE INVENTORY--VEHICLE DESCRIPTION

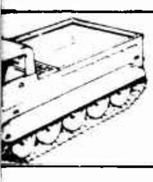
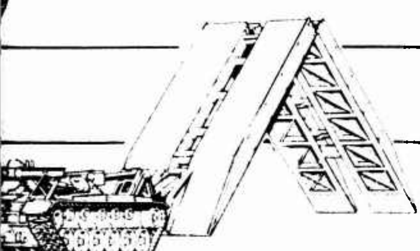
	Mission	Existing and Projected Systems	
		Current: 1973-1979	Projected: 1980-1990
	Designed for a specific fighting purpose. Provide a high degree of cross-country mobility, armor protection, and firepower for filling various combat roles.	Armored reconnaissance scout vehicle (ARSV). Armored reconnaissance airborne assault vehicle (ARAAV). Main battle tank (MBT). Combat engineer vehicle (CEV). Mechanized infantry combat vehicle (MICV). Self-propelled artillery. Anti-tank. Air defense system. Missile rocket artillery.	High agility tank. Medium tank. Elevated missile launcher. ACV weapons system (ACVWS-90). Low-altitude air defense gun system (LOFAADS). Rapid-fire area saturation system (RFASS). Self-propelled artillery. Missile system target illuminator controlled/elevated target acquisition system (MISTIC/ELTAS).
	Designed primarily for use by forces in the field in direct connection with or support of combat or tactical operations.	High-mobility wheeled. Standard mobility wheeled. Armored personnel carrier (APC). Cargo carrier. Commercial vehicles (which may fill any category of mobility--high, standard, or support).	Tactical high-mobility wheeled vehicle fleet. Tactical standard mobility wheeled vehicle fleet. Commercial vehicles. High mobility tracked utility.
	Mobility support.	Recovery vehicles. Snow vehicles. Missile loaders. Container transporter. Fluid transporter. Ambulance. Wrecker. Trailer transporter. Small tactical air-mobile platform (STAMP). Heavy equipment transporter. Shops, shelter vans. Electric equipment carrier. Trailers and sleds. Lighter, amphibious, resupply, cargo (LARCS). Landing vehicle, personnel, tracked (LVTP-7). Lighter, amphibian, 25-ton (Voyager).	Aerial platforms. Advanced amphibian assault landing vehicle. Trans-hydrocraft. Lighter, amphibious, 60-ton, ACV. Lightweight, maintenance/recovery vehicle.
	Handle, stack, move, and otherwise manipulate military supplies of all types.	Fork lifts. Unitization system. Transportation equipment. Control and identification equipment. POL handling systems. Ship mooring and off-loading equipment. Pipelines. Containers. Rolling fluid transporter.	Rough-terrain cargo handler. Prepackaged support facility.
	Construction, maintenance, and repair of facilities to support military operations.	Combat support. Helicopter transportable. Rough terrain cranes. Heavy construction equipment.	Electric-drive family. Commercial family, CCE.
	Allow passage of forces across wet and dry gaps, rivers, and other inland waterways without loss of momentum.	Armored vehicle launcher-bridge family. Mobile assault bridge ferry. Floating bridge. Fixed tacti[illegible] bridge. Rafts.	U.S.-U.K. FRG bridge system, 1985.
	Necessarily employed by land mobility vehicle and equipment to permit achievement of their mission or task.	Fuels. Lubricants. Power transmission fluids. Compounds.	Substitute fuels.
	Nullify natural and enemy emplaced barriers to permit access to areas denied.	Combat and combat support vehicle equipment. Dismounted unit support. Fuel-air explosive, FAE. Foam-in-place mats. Advanced minedetectors. Mine removal plows, PLOW	Counterbarrier systems.
	Expedient road construction, reconstruction and maintenance to provide a path for military ground mobility.	Expedient surface. High-speed excavators.	Surfacing process. Ground treatment.

TABLE B-7. ARMY VEHICLE INVENTORY (Approximate Quantity and Cost of Vehicles)

Major Group	Vehicle Class	Quantity	1971 Dollars (Millions)
Combat Vehicles 2.5% of number 31% of dollars	Tanks	9,000	2,000
	Scout & Reconnaissance	4,000	200
	SP Guns	3,000	500
	Others: Airborne Assault Combat Engineering, etc.	4,000	400
Tactical & Transport Vehicles 45% of number 43% of dollars	High-Mobility Wheeled	40,000	800
	Standard-Mobility Wheeled	300,000	3,000
	Tracked	20,000	800
Nontactical 19% of number 6% of dollars	Limited-Mobility Commercial	150,000	600
Highway Construction 5% of number 9% of dollars	All Types	40,000	900
Special-Purpose 1.3% of number 6% of dollars	Recovery River Crossing, etc.	10,000	600
Trailers 28% of number 5% of dollars	All Types	220,000	500
TOTALS		800,000	10,300

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TABLE B-8. DIESEL ENGINE DATA

Maker	Type	Number of Cylinders	Weight (Pounds)	Horse-power	Lb/hp	hp/Cylinder
Mercedes Benz	OM 636	4	355	36	9.8	9
	OM 314	4	660	62	10.6	15
	OM 352	6	850	95	9.0	16
	OM 327	6	1,300	122	10.7	20
	OM 346	6	1,700	150	11.6	25
	MB 846A	6	3,920	240	16.4	40
	MB 833A	6-v	2,610	270	9.7	45
	MB 837A	8-v	3,100	360	8.6	45
	MB 838A	10-v	3,710	450	8.2	45
Hercules	D 3000	6	780	114	6.8	19
	D 1700	3	570	50	11.4	19
	DJ 60	2	270	14.6	18	
	DJ 120	4	438	27.5	16	
Detroit Diesel	6 U53	6	1,540	195	7.9	33
	6-71	6	2,150	238	9.0	40
	6-71(M)	6	2,740	280	9.8	47
	3-53	3	1,005	101	10	34
	4-53	4	1,190	140	8.5	35
	4-71	4	1,750	160	11	40
	8V53	8	1,900	247	7.7	31
	8V71	8	2,345	260	9	33
	12V71	12	3,300	475	7	40
International	MD 301	6	1,150	95	12	16
	MD 361	6	1,700	103	15	19
	MD 188	4	850	60	14	15
Cummins	C180	6	1,660	180	9.2	30
	V8185	8	1,210	185	6.5	23
	C190	6	1,670	190	8.7	32
	V6-200	6	1,690	200	8.5	33

TABLE B-8. (Continued) DIESEL ENGINE DATA

Maker	Type	Number of Cylinders	Weight (Pounds)	Horse-power	Lb/ hp	hp/ Cylinder
Cummins (Cont'd)	V8E-235	8	2,080	235	8.7	29
	NHC-250	6	2,460	250	9.8	42
	V8-265	8	2,080	265	7.9	33
	V 903	8	2,160	320	6.7	40
Conti-nental	F227	6	501	84.5	6.0	14
	F245	6	564	95.5	5.9	16
	M330	6	800	118	6.8	20
	B427	6	950	137	7.0	23
	G-176	4	520	65	8.0	16
	Y-112	4	290	33	8.7	8
	2-145	4	410	54	7.6	13
	L-278	6	1,435	178	8.0	30
	G-193	4	525	70	7.5	17
	2-134	4	340	50	6.8	13
SEMT	PCL	Series			24	500
	PCV	Series			19	500
Dorman	4D A/M	4	825	31		
	6D A/M	6	1,050	46		
Jenbach	JW Series	1			30	50
		2			18	50
		4			13	50
	Multi:	i.e. >4			10	50
	4M Series	4			22	125
		6			17	125
		8			15	125
		12			13	125
Selzer	240148				27	550
	RD 56				61	910

Page 2 of 3

TABLE B-8 (Continued) DIESEL ENGINE DATA

Maker	Type	Number of Cylinders	Weight (Pounds)	Horse-power	Lb/ hp	hp/ Cylinder
Selzer (Cont'd)	RND 76				67	2,000
	RND 90				62	2,900
	RND 105				65	4,000
Ruston	AO Series	6, 8, 9			20	500
		12			17	500
		16			16	500
Deutz	F1L 410	1	242	13	19	13
	F2L 410	2	330	25	13	13
	F2L 812	2	584	26	22	13
	F3L 812	3	661	45	15	15
	F4L 812	4	694	60	12	15
	F6L 812	6	904	90	10	15
	F4M 716	4	1,700	140	12	35
	F6M 716	6	2,282	210	11	35
	F8M 716	8	3,274	250	13	31
	F12M 716	12	4,012	420	10	35
	BV6M 540	6	54,013	2,400	23	400
	BV8M 540	8	67,240	3,200	21	400
	BV12M 540	12	84,770	4,800	18	400
	BV16M 540	16	104,719	6,400	16	400
Lycoming	W21	1	112	4	28	4
	W51	1	150	6	25	6
	W62	1	216	9	24	9
	W71	1	217	11	19	11
	W32	2	306	18	17	9
	W42	2	313	20	16	10
	W34	4	433	36	12	9
	W44	4	433	40	11	10

Page 3 of 3

APPENDIX C

GENERAL VEHICLE CHARACTERISTICS AND PROPULSION SYSTEM NEEDS

CONTENTS

APPENDIX C

GENERAL VEHICLE CHARACTERISTICS AND PROPULSION SYSTEM NEEDS

C.1 APPROACH

The purpose of this Appendix is to examine those general characteristics of high-performance military surface vehicles which determine propulsion system requirements. The goal is to be able to write general specifications for the propulsion system in terms of power output, weight and volume requirements for classes of vehicles without the necessity of going into detailed design. Such an analysis is necessary for guidance and assessment of Technology Base activities, since by definition these programs are not related to an actual hardware development. The approach that is used here is to evaluate the overall constraints in designing a generalized vehicle and to refer to actual design experience for the results of trade-offs between conflicting demands.

The generalized vehicle concept is shown in Figs. C.1 and C.2 together with the notation that will be used. As a general rule, capital letters are used for the individual quantities and lower case subscripts for the specific identification or location of the quantity, e.g., W = weight, W_e = engine weight. The relationships between component characteristics, vehicle parameters and vehicle performance specifications are not complicated. Care must be taken, however, to identify quantities properly. For example, "propulsive power" as commonly used can mean either the power output of the engine, P_e, or the power delivered by the thruster, $P_t = P_e \eta_x \eta_t$. Symbols rather than descriptive words will be used in the text to avoid these possible areas of confusion.

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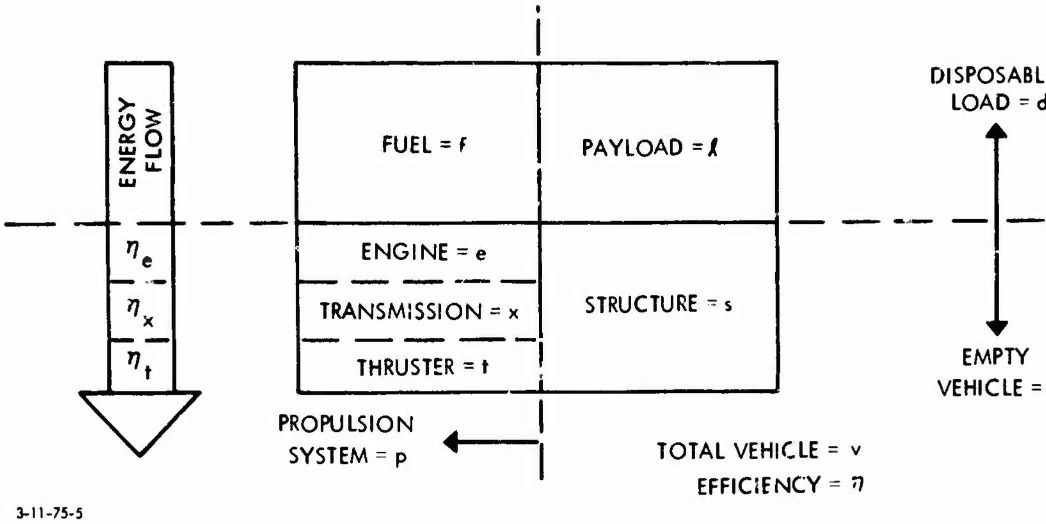

FIGURE C-1. Vehicle Concept and Notation Method

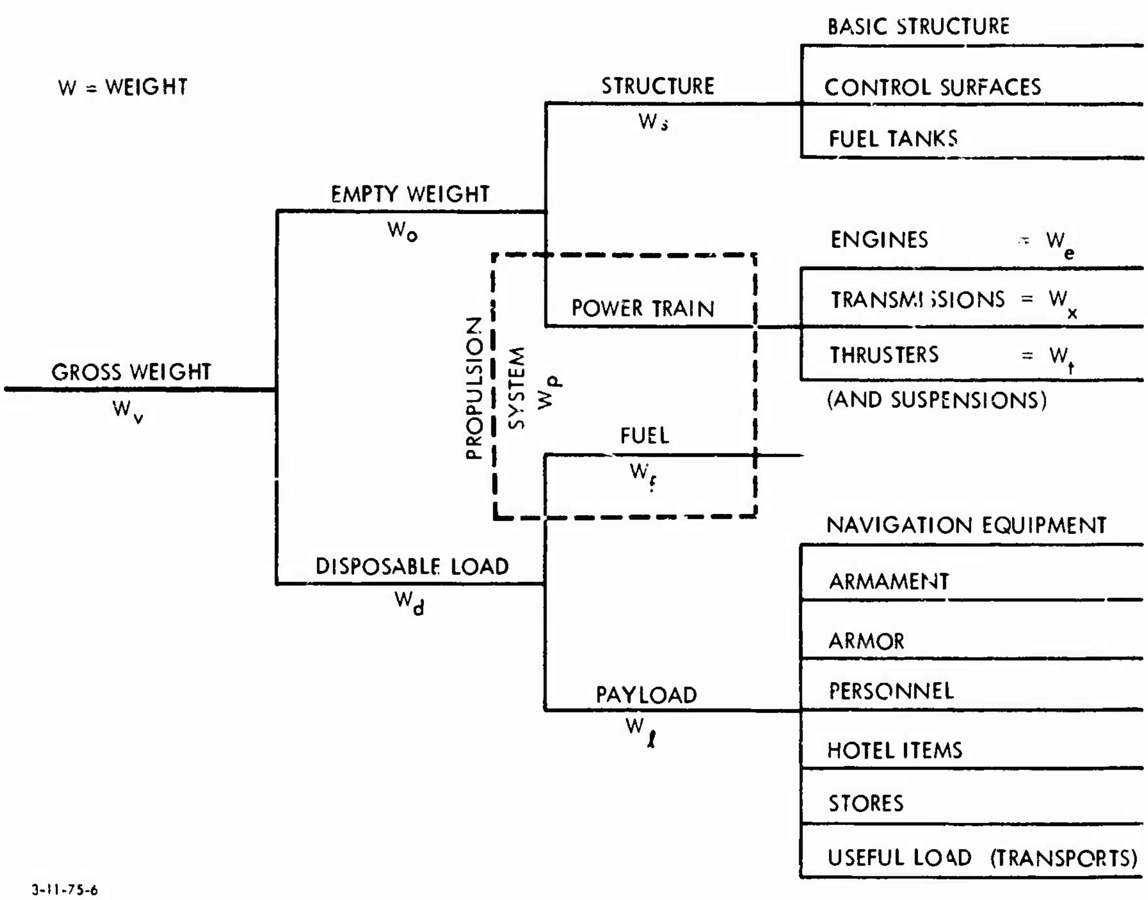

FIGURE C-2. Weight Breakdown and Nomenclature

In addition, the parts of the vehicle must be defined as shown in Fig. C.2. This creates some difficulties in referring to specific design results since it is not always possible to convert other weight breakdowns exactly to the one required here from the information that is given. One major distinction that should be noted is in the definition of payload. The ground rule adopted here is that payload consists of everything the vehicle carries that does not directly contribute to its ability to operate as a moving platform.

C.2 PERFORMANCE CHARACTERISTICS

To analyze the propulsion system needs for this generalized vehicle, the only performance characteristics that are needed are the specific power (P_e/W_v) and the specific resistance ($P_{cr}/W_v V_{cr}$) of the vehicle. It was pointed out by Karman and Gabrielli (Ref. C.1) that specific power is a measure of top speed and specific resistance is a measure of transport efficiency for all kinds of vehicles. Since that paper was published 25 years ago, these parameters have been used by a number of authors (e.g., Ref. C.2) to evaluate and compare vehicle types in a general way. The approach used here is to note that these vehicle parameters depend only on the specific weight and the specific fuel consumption of the propulsion system, and on the weight distribution in the vehicle as a whole.

The range of values of specific resistance and specific power is shown in Fig. C.3 for a wide range of vehicles. This is the type of data used in Ref. C.1 and it should be noted that the lines are boundaries of attained values for classes of vehicles and are <u>not</u> performance curves for a given vehicle. The point to be made here is simply that specific power and specific resistance are predictable performance parameters for a given class of vehicles. The ranges of these parameters of interest for future military surface vehicles are discussed in Section 2.

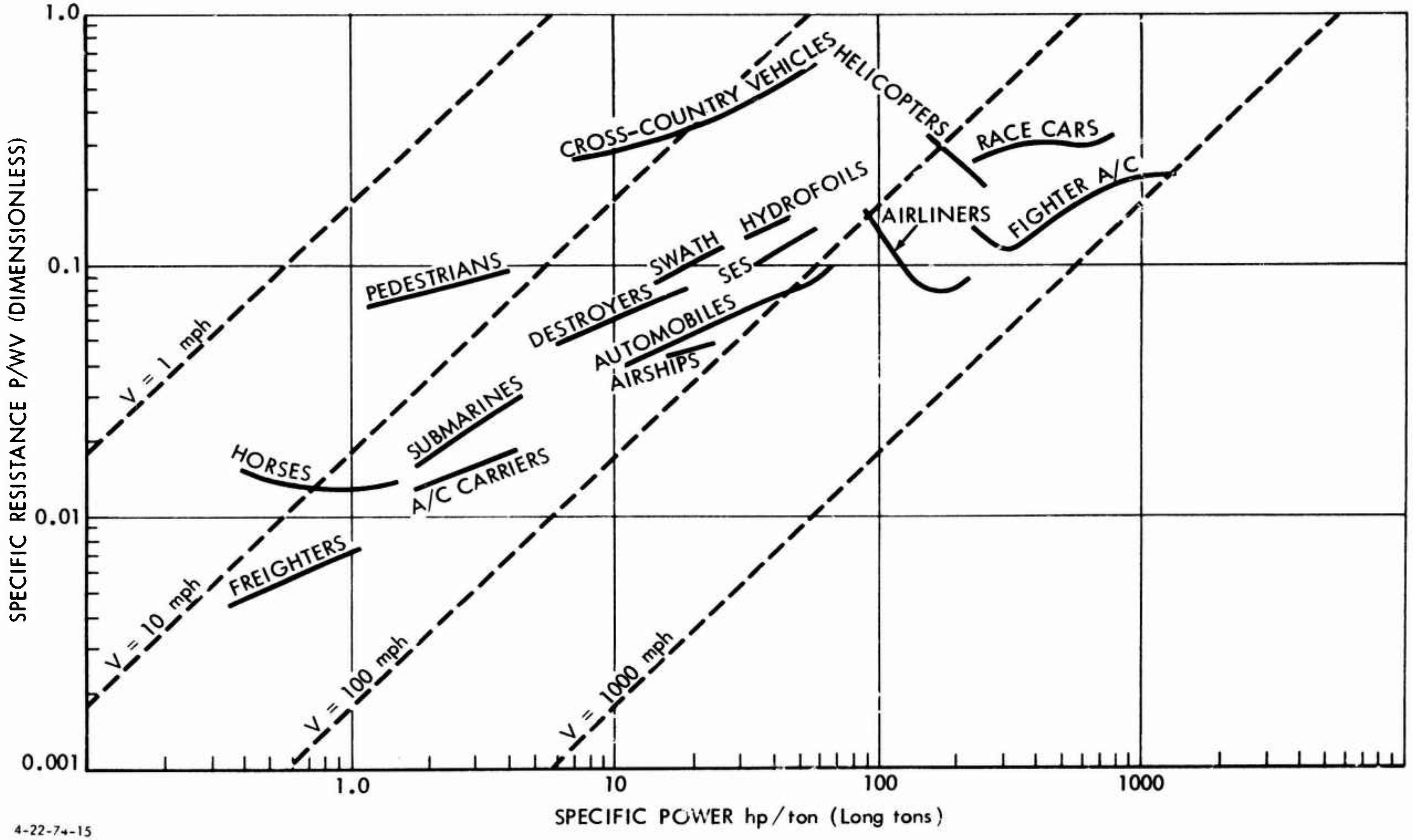

FIGURE C-3. Variety of Vehicles Compared in Terms of Their Basic Performance Parameters

C.3 WEIGHT DISTRIBUTIONS

The remaining data that are needed are the limits on the weight fractions that can be assigned to the propulsion system for high-performance military vehicles. From an examination of design results from a number of sources (Refs. C.3, C.4, C.5, C.6) the following general limits appear:

<u>For all high-performance vehicles</u>

- There is an upper limit of $W_p W_v \doteq 0.40$ for all military vehicles. It should be noted that many racing vehicles have W_p/W_v greater than 0.40 but they characteristically carry very little payload. The reason for the lower limit on military vehicles is that they must carry a reasonable payload fraction or they become too expensive to acquire and operate as a class of vehicles.

<u>For sea vehicles</u>

- In displacement ships the upper limit is approached in small oceangoing combat ships. To meet range requirements these vessels need $W_f/W_v \doteq 0.20$ to 0.25, leaving 15 to 20 percent of vehicle weight for the rest of the propulsion system, i.e., engine, transmission and thruster. As displacement ships get larger, specific power requirements are reduced and W_p/W_v can be reduced to reach about 0.10 in carriers.
- In high-speed escort designs maximum values of W_p/W_v are needed together with maximum W_f/W_v allowances. Designs have allocated about two thirds of propulsion system weight to fuel, leaving 10 to 15 percent of vehicle weight for the engine, transmission and thruster combined.
- In coastal high-performance ships, range is not so important. As a result, fuel requirements are reduced and W_p/W_v has a maximum value of 0.30. For the special ship-to-shore mission, range is even further reduced and payload requirements increased, to give $W_p/W_v \approx 0.20$.

For land vehicles

- Heavy tracked vehicles have $W_p/W_v \approx 0.35$. However, the track and suspension are very heavy. Typically, $W_t/W_v = 0.20$ or slightly more. This leaves about 15 percent of W_v for engine, transmission and fuel. Range requirements are small and fuel is only 2 to 3 percent of W_v.
- For light tracked vehicles W_p/W_v can reach 0.40, which allows up to 20 percent of W_v to go for engine, transmission and fuel.
- For high-mobility wheeled vehicles the thruster is much lighter, $W_t/W_v \doteq 0.10$. However, these are support vehicles and to optimize payload capabilities W_p/W_v is held to about 0.25. Hence about 15 percent of W_v is allowed for engine, transmission and fuel.

These weight distribution limits can be used with specific power requirements to get specific weight ranges for acceptable propulsion systems, as is done in Table 2-6. In addition, in conjunction with specific power requirements, they can be used to relate range and specific fuel consumption as discussed in Section 2.3.

C.4 VEHICLE COSTS

Costing by weight is common practice within a given class of vehicles. However, in comparing widely different types of vehicles costing by weight runs into difficulties. For example, how can an 8,000-ton frigate cost more than a 400,000-ton supertanker? One observation is that the frigate has roughly twice the installed horsepower of the tanker and, since it is only 1/50 of the gross weight of the tanker, it has a specific power 100 times that of the tanker. In addition to the direct cost of buying and installing more power, the vehicle with high specific power must be built much more ruggedly without exceeding structural weight fraction limits (a maximum of around 0.35 W_v). This forces use of more expensive structures for high-powered vehicles. For example, the high-speed escorts (>50 knots) are forced toward aircraft techniques for much of their structure.

It is proposed here that specific power is an effective measure of these higher costs. This leads to a formulation of acquisition costs in this way

$$\text{Vehicle Cost} = \begin{pmatrix} \text{Basic cost} \\ \text{proportional to} \\ \text{empty weight} \end{pmatrix} + \begin{pmatrix} \text{Added cost} \\ \text{proportional to} \\ \text{specific power} \end{pmatrix}$$

which takes the explicit form

$$\$_V = W_V \left[1000 \frac{W_o}{W_V} + Q^{-0.33} \left(1200 \frac{P_e}{W_V} \right) \right]$$

where Q is the number of vehicles built and the constants were determined by correlating vehicle acquisition cost data as shown in Fig. C.4.

These results are intended only to provide a first-order estimate of vehicle costs for evaluating conceptual vehicles. Note that for high-powered vehicles which are built in small quantities the second term of the cost estimating equation dominates, while for low-powered vehicles the first term dominates. Thus in comparing the frigate and the supertanker we see that the cost of the frigate is largely determined by its power requirements, while the cost of the tanker is mainly due to its large structure. Other implications of this formulation of cost factors are discussed in Section 2.4.2, Cost Limits.

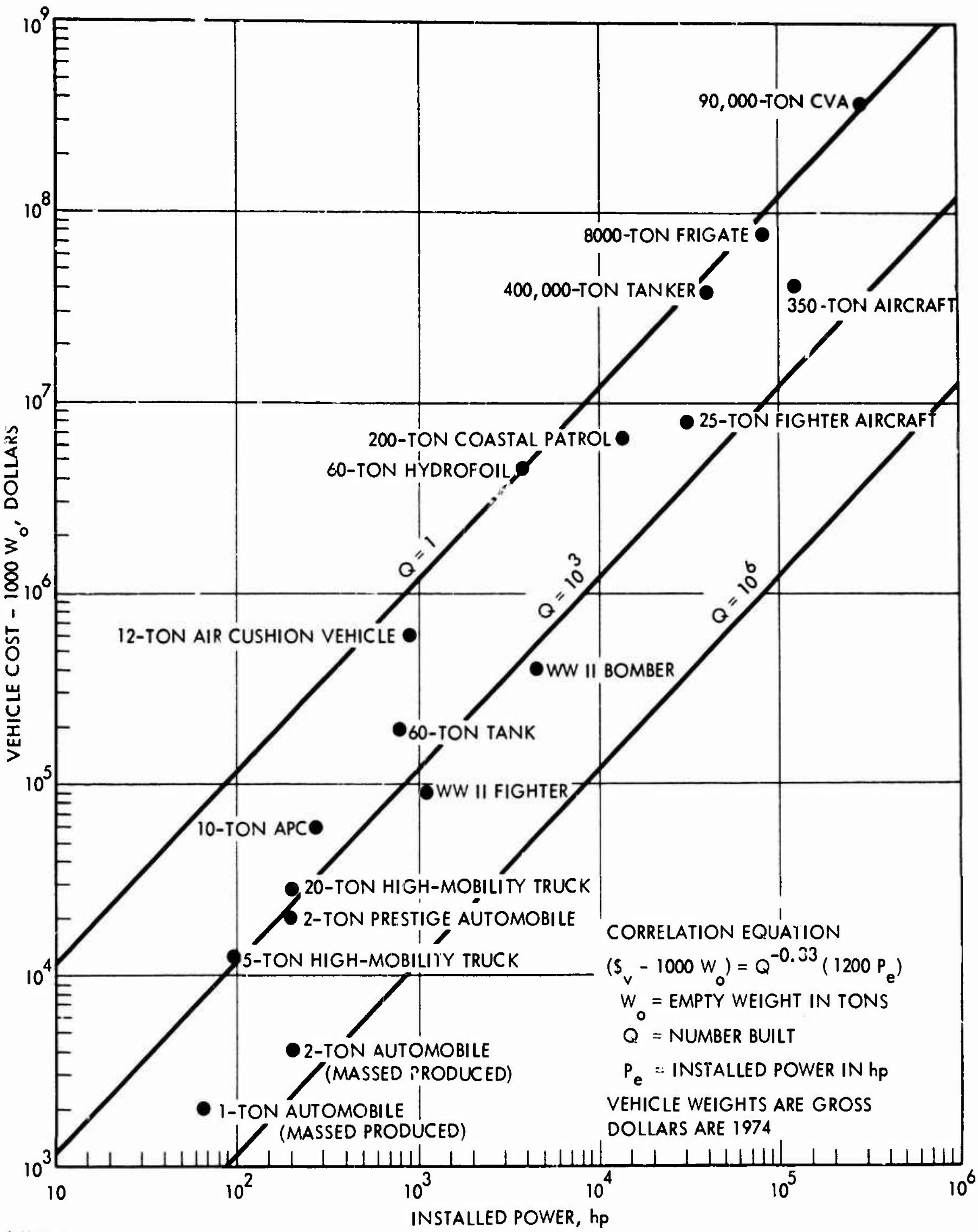

FIGURE C-4. Acquisition Costs for Bare Vehicles

REFERENCES

C.1. G. Gabrielli and T.H. von Karman, "What Price Speed?--Specific Power Required for Propulsion of Vehicles," Mechanical Engineering, Vol. 72, No. 10, October 1950.

C.2. Stevens Institute of Technology, Notes on the Power-Speed-Weight Relationships for Vehicles, Technical Memorandum No. 97, K.S.M. Davidson, March 1951.

C.3. Handbook of Army Material, U.S. Army Ordnance Center and School, Aberdeen Proving Ground, Publication ST9-159, May 1972.

C.4. Jane's Fighting Ships, 1974-1975, New York: McGraw-Hill, 1974.

C.5. U.S. Army, Characteristic Data Sheets.

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APPENDIX D

POWERING SEA VEHICLES

Philip Mandel

CONTENTS

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APPENDIX D

POWERING SEA VEHICLES

D.1 INTRODUCTION

The parameter specific thrust power (i.e., thrust hp/ton) is plotted as a function of speed, with gross weight as a parameter for a number of sea vehicles in Figs. D.1, D.2, and D.3. The same results are cross-plotted for specific thrust power as a function of gross weight with speed as a parameter in Figs. D.4, D.5, and D.6. Thrust power per ton of gross weight, P_t/W_v is defined as

$$\frac{P_t}{W_v} = \frac{\eta_{xt} P_e}{W_v} = \frac{6.87 \; V_K D_T}{W_v \; (2240)} \quad , \tag{D.1}$$

where

P_t = thrust power (in horsepower) at speed V_K*

P_e = engine power output at V_K

η_{xt} = overall transmission and thruster efficiency

W_v = gross weight in long tons

*Note that the term thrust power, as used in this report, is the power delivered by the propulsors (including lift fans, if applicable). It therefore differs from the definition of thrust power as used by the Naval Architect which includes some of the power changes caused by the interaction of the propulsor with the hull of the vehicle.

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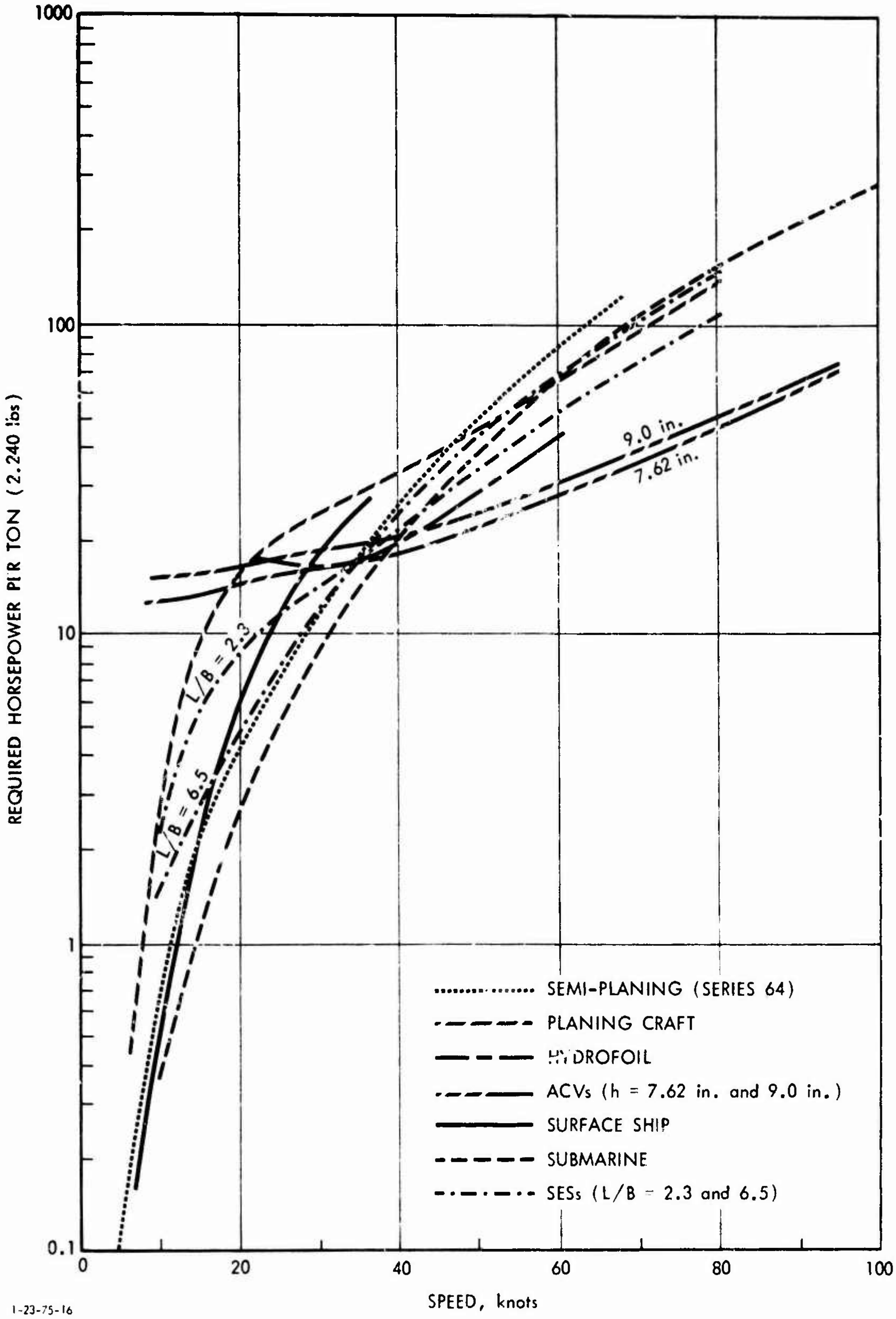

FIGURE D-1. Required Power per Ton for 100-Ton Vehicles

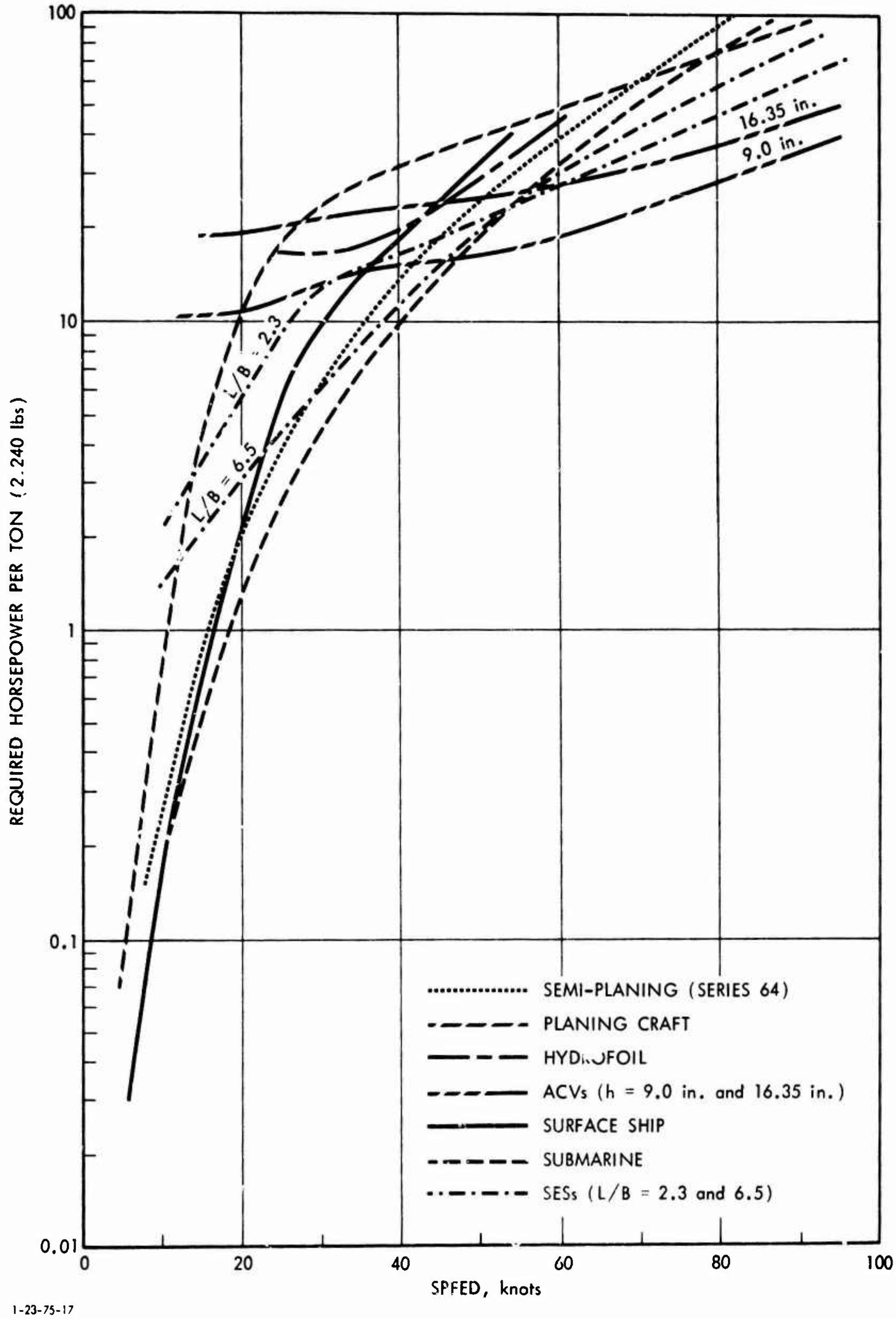

FIGURE D-2. Required Power per Ton for 1,000-Ton Vehicles

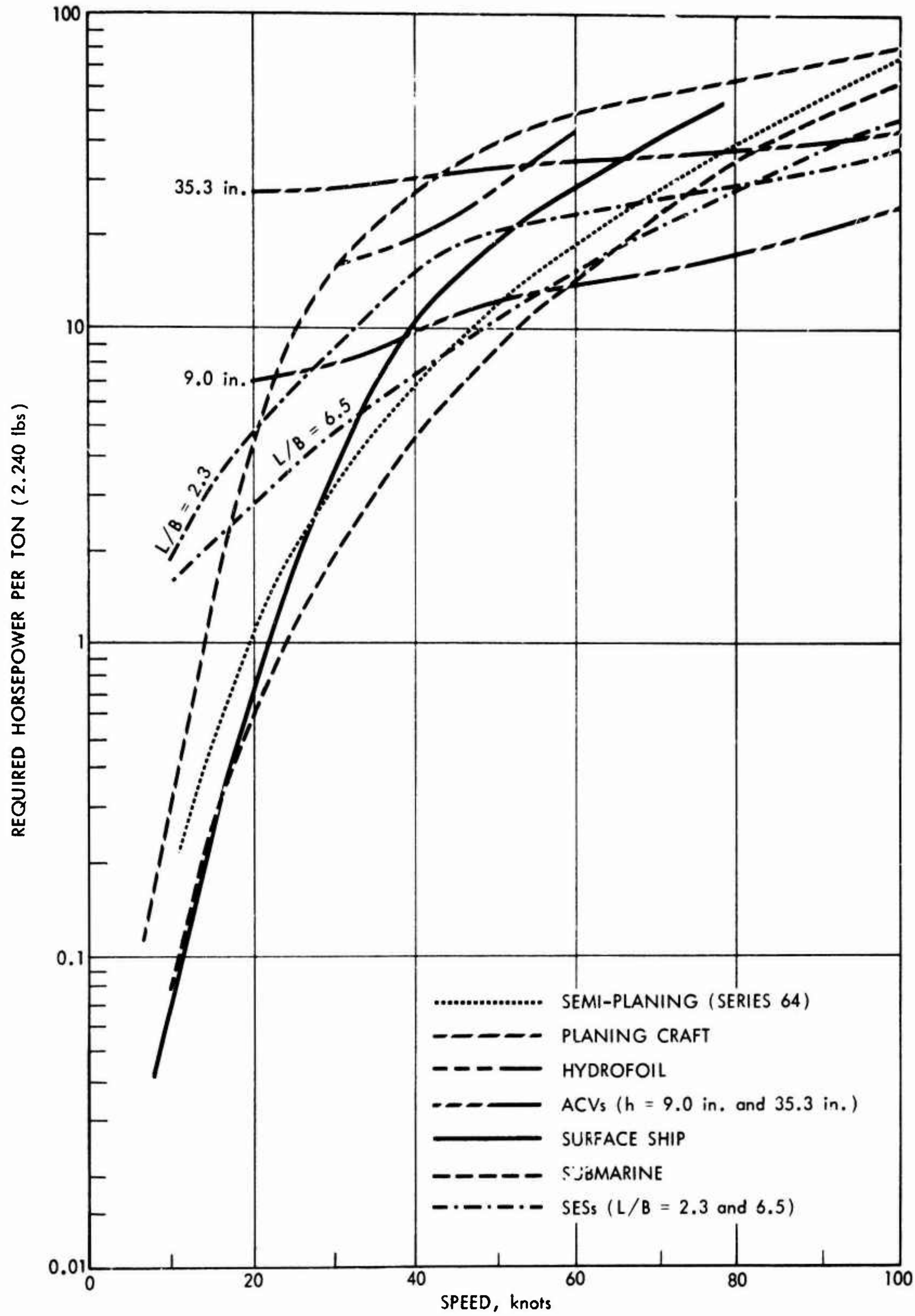

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FIGURE D-3. Required Power per Ton for 10,000-Ton Vehicles

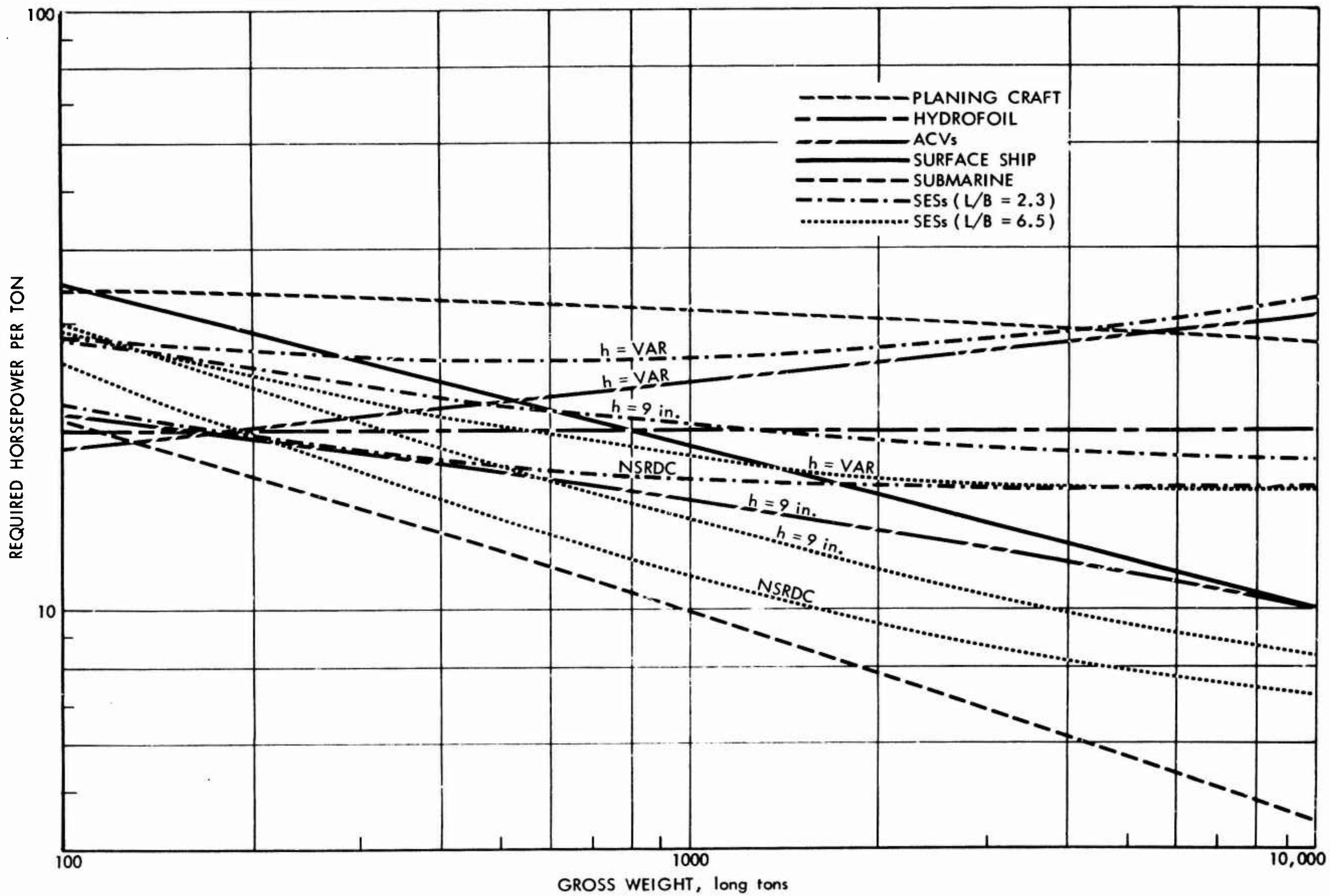

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FIGURE D-4. Specific Power as a Function of Gross Weight for V = 40 Knots

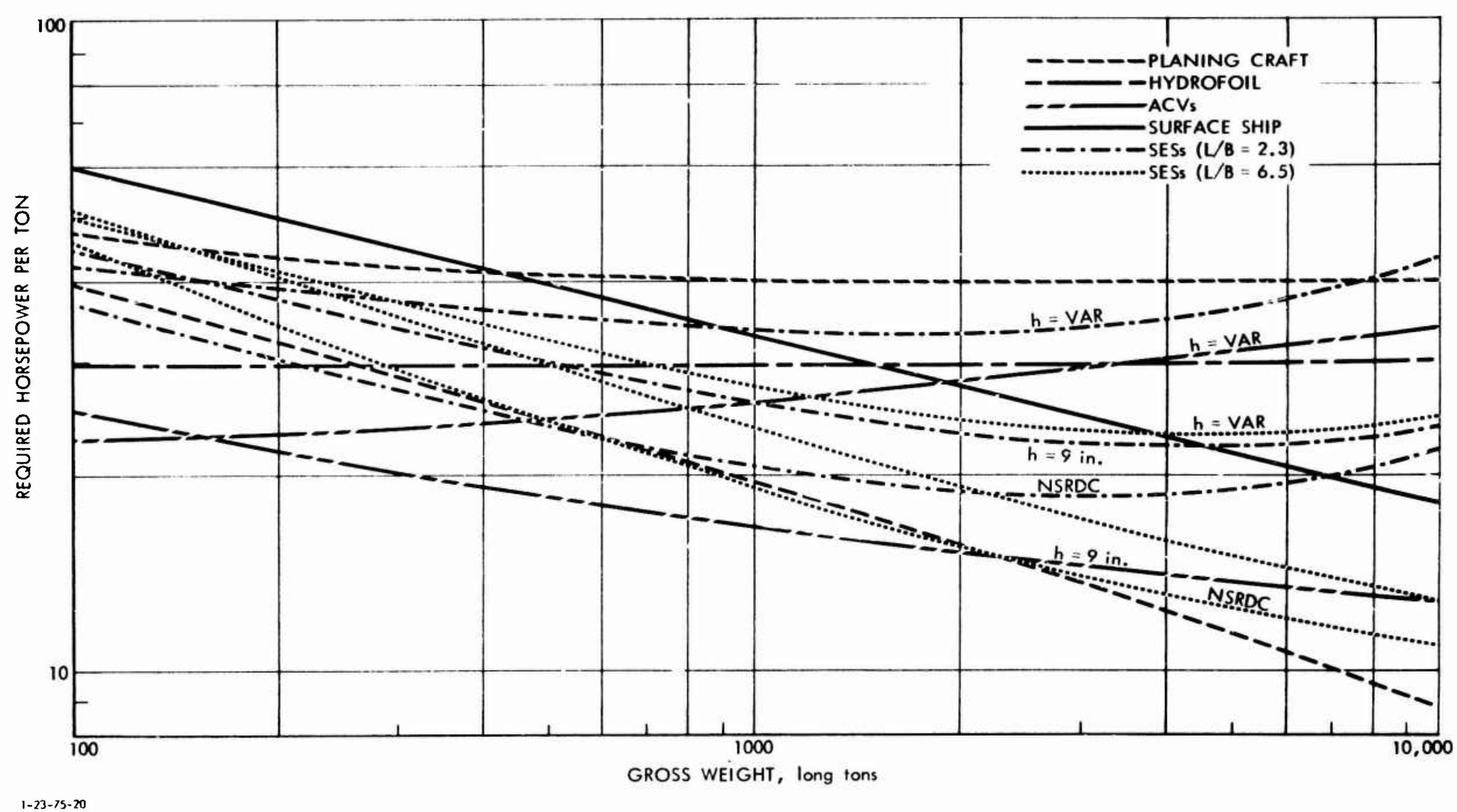

FIGURE D-5. Specific Power as a Function of Gross Weight for V = 50 Knots

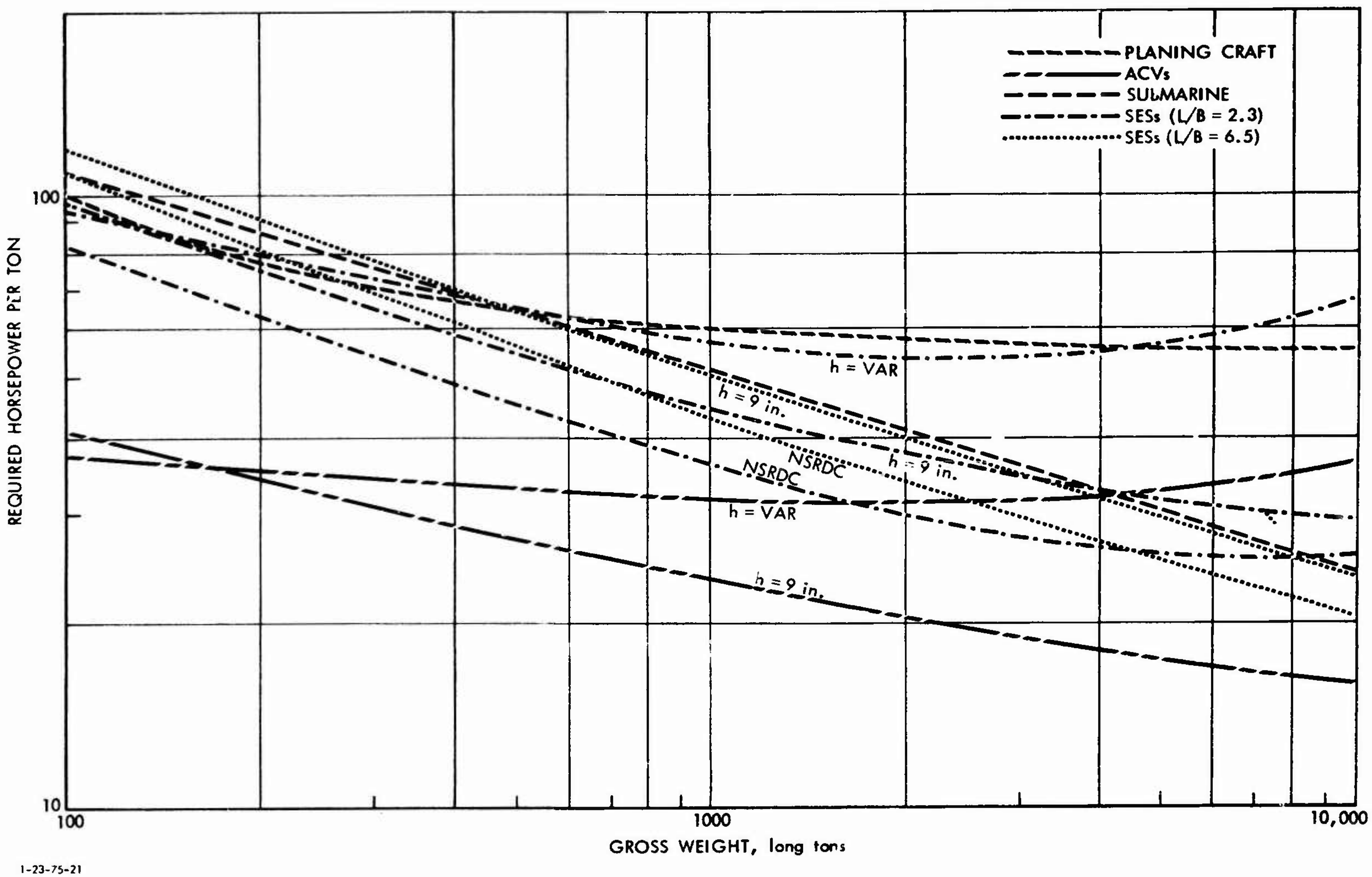

FIGURE D-6. Specific Power as a Function of Gross Weight for V = 70 Knots

V_K = speed in knots

D_T = total drag, in lbs, of the vehicle (new) with no appendages such as rudder, shaft supports, roll-control devices, etc., included.

The omission of the drag of the items listed in the definition of D_T means that the thrust power data plotted are underpredicted compared to reality. The extent of this underprediction may amount to 30 percent or more of the bare hull drag for small, high-speed vehicles. The drag definition also excludes the effect of fouling. Even with modern antifouling paints, the drag of sea vehicles will increase 15 percent to 20 percent over a period of two years out-of-dock. The drag data used in this report apply to new, freshly painted hulls.

Seven vehicle types are included in the P_t/W_v plots of Figs. D.1, D.2, and D.3. The semi-planing vehicles (Series 64) are not included in Figs. D.4, D.5, and D.6. For one of the vehicle types, the Surface Effects Ship (SES), data are shown for two different length-to-beam (L/B) ratios and for three different values of the vertical clearances, h, between the water surface and the bottom of the closures forming the forward and aft ends of the air cushion (see Section D.7). For the Air-Cushion Vehicles (ACV), data are shown for two values of the vertical clearance (see Section D.6).

Each of the curves represents a single vehicle type and a single configuration of that type. In other words, minimum drag forms at each speed or at each gross weight were not used in forming the drag estimates. Rather, for each vehicle type (except the SESs and the ACVs) a single configuration representing a reasonable compromise over the whole range of speeds and gross weight was selected. The particulars of the configurations selected for each vehicle type are included in Sections D.2 through D.7.

Note that no single standard was used in selecting the configuration for each vehicle type. For example, the configuration selected for the surface ship (Section D.2) is a practical, but not an eminently low-drag, configuration. In contrast, the configuration used for the semi-planing ship with its exceptionally low volumetric coefficient is not a practical configuration. Nevertheless, it represents a limit of what can be achieved with more or less conventional ships at high speed.

For all vehicle types, vehicle size was related to vehicle gross weight (or vice versa) by a standard rule. This rule is that each of the vehicle dimensions of the larger vehicle is λ times larger than the corresponding dimensions of the smaller vehicle where

$$\lambda = (W_L/W_S)^{1/3} \quad , \tag{D.2}$$

and where

λ = scale ratio for linear dimensions (larger to smaller)

W_L = weight of larger vehicle

W_S = weight of smaller vehicle in same unit as W_L.

This rule is mandatory for buoyantly supported vehicles like ships and submarines if geometric similitude among vehicles of different sizes is to be maintained. It is not mandatory for geometrically similar hydrofoils, planing craft, ACVs or SESs. However, it was used for these vehicle types as well as ships and submarines, as will be shown in the following sections.

D. SPECIFIC POWER FOR SURFACE SHIPS AND SUBMARINES

The basic equations for the lift-to-drag ratio (W/D_T) of buoyantly supported vehicles for use in Eq. (D.1) are given by Eqs. 7.8 and 7.9 of Ref. D.1. Section 7.2, "Buoyantly Supported Vehicles," of that reference discusses the effects of changes in velocity and size of both surface ships and submarines. Equation 7.8 of Ref. D.1 is as follows:

$$\frac{W}{D_T} = \frac{\Delta}{\frac{1}{2}\rho \; C_T \; SV^2} \quad , \tag{D.3}$$

where

W = gross weight, in lbs = Δ

Δ = buoyant force, in lbs = $\rho g \nabla$

∇ = underwater volume, in cu ft

ρ = mass density of fluid, in lbs sec^2/ft^4

g = gravity acceleration, in ft/sec^2

C_T = total drag coefficient = frictional drag coefficient plus residual drag coefficient

S = wetted surface area of vehicle, in sq ft

V = vehicle velocity, in ft/sec

D_T = total drag, in lbs

Several important effects of Eqs. 7.8 and 7.9 of Ref. D.1 are observable in Figs. D.1, D.2, and D.3. These effects are

1) An increase in speed for any size severely degrades W/D_T and increases P_t/W_v. The penalty with increasing speed is much more severe with surface ships than with submarines in the Froude number (F_n)* range:

$$0.15 \leq F_n \leq 0.5 \quad ,$$

but the penalty exists at all speeds with both ship types.

2) Above a Froude number of 0.5, the percentage increase in P_t/W_v for a given increase in speed is less for the surface ship than for the submarine. However, the penalty in terms of actual P_t/W_v is still much larger for the surface ship than for the submarine, even at $F_n \geq 0.5$.

---

*$F_n = V/\sqrt{gL}$, where V = speed, g = gravity acceleration, L = vehicle length. See Table D.1 for relation of F_n to speed for the surface ships of Figs. D.1 through D.3.

3) An increase in size with no change in speed significantly decreases P_t/W_v for both surface ships and submarines. At $0.15 \leq F_n \leq 0.5$, the benefit is much more pronounced for surface ships than for submarines, although the overall beneficial effect persists at all speeds.

TABLE D-1. SURFACE SHIP CONFIGURATION DATA

Characteristic	Weight, long tons		
	100	1,000	10,000
Length, water line ft	127	274	588
Beam, water line ft	11.85	25.5	54.9
Draft, ft	3.95	8.5	18.3
Wetted Area, sq ft	1,693	7,857	36,500
Volumetric Coefficient, Underwater Volume/Length^3, C_v	0.0017	0.0017	0.0017
Prismatic Coefficient, C_p	0.64	0.64	0.64
Maximum Section Coefficient	0.925	0.925	0.925
Speed at F_n = 0.5, knots	18.9	27.8	40.8

Parent Vehicle	
Name	--
Country	--
Reference	1964 S.N.A.M.E. Trans., Fig. 4, p. 380
Weight	--
Length	--
Volumetric Coefficient	0.0017
Prismatic Coefficient	0.56, 0.60, 0.064, 0.068, 0.072
Beam-to-Draft Ratio	3.00
Midsection Coefficient	0.925

The specific configuration and the data source used for the surface ship of this report are given in Table D-1. The same information for the submarine is presented in Table D-2. For surface ships, the volumetric coefficient $C_v = \nabla/L^3$,

where

∇ = underwater volume

L = waterline length,

and the prismatic coefficient $C_p = \nabla/LA_m$,

where

A_m = area of maximum section,

are the two most important configuration descriptors. A low value of C_p is very beneficial at speeds in the vicinity of $0.25 \leq F_n \leq 0.4$ and not dominantly influential at other speeds. On the other hand, a low value of C_v is very important at $F_n \geq 0.4$, because of greatly reduced residual drag, and a high value is preferable at $F_n \leq 0.3$ because of reduced frictional drag. The values of C_v and C_p selected for Table D-1 are fairly close to those of a modern destroyer. Ordinary surface ships with volumetric coefficients less than 0.0017 are rare indeed (see Section D.5).

On the other hand, because there is no wave drag associated with submarines, their drag is reduced by large values of C_v at all speeds. This arises from the impact of C_v on wetted surface area. A high value of C_v results in smaller wetted surface per unit gross weight, hence frictional drag is reduced. For this reason, the submarine C_v value selected for Table D-2 is over an order of magnitude larger than that of the surface ship.

Note that a submarine's wetted area includes the top of the submarine, whereas the wetted area of a surface ship includes only its sides and bottom. Thus, if the submarine of Table D-2 had a volumetric coefficient like that of the surface ship, its wetted area would be about 25 percent larger than that of the surface ship. However, with a C_v value of 0.0188 vs. 0.0017 for the surface ship, the submarine wetted areas are actually less than those of surface ships of comparable weight.

TABLE D-2. SUBMARINE CONFIGURATION DATA

Characteristic	Weight, long tons 100	1,000	10,000
Length, ft	57	123	262
Diameter, ft	11.4	24.6	52.4
Wetted Area, sq ft	1,540	7,150	33,200
Volumetric Coefficient, Volume/Length^3, C_v	0.0188	0.0188	0.0188
Prismatic Coefficient, C_p	0.60	0.60	0.60

Parent Vehicle	
Name	--
Country	--
Reference	1960 S.N.A.M.E. *Trans.*, Table 1, p.631
Weight	--
Length	--
Length-to-Diameter Ratio	4.0 to 17.5
Prismatic Coefficient	0.55 to 0.84
Wetted Area	--

In comparing the P_t/W_v data for submarines with those of other vehicles, including surface ships, it is important to bear in mind that the drag of appendages is not considered in this report. Submarines with their large control surfaces (for both vertical and horizontal maneuvering), their large bridge fairwaters, etc., have larger appendage drag than any other vehicles, amounting to 60 percent or more of the bare hull drag. Thus, the favorable comparison of submarines to other vehicles in terms of their bare P_t/W_v data should be viewed with caution.

It is evident from Figs. D.1, D.2, and D.3 that among the practical surface vehicles (excluding the Series 64 of Section D.5), surface ships have the most favorable P_t/W_v values at low speeds of all the vehicles considered. They hold their advantage to

17.5 knots at 100 tons

22.5 knots at 1,000 tons

34 knots at 10,000 tons.

D.3 SPECIFIC POWER FOR HYDROFOILS

The basic equation for the W/D_T ratio of hydrofoil craft and of airplanes for use in Eq. (D.1) is given by Eq. 7.19 of Ref. D.1. Section 7.3, "Dynamically Supported Vehicles; Aircraft and Hydrofoils," of that reference discusses the effects of changes in velocity and of size of hydrofoil craft. Equation 7.19 of Ref. D.1 is as follows:

$$\frac{W}{D_T} = \frac{1}{\dfrac{W/A}{a\pi \frac{1}{2}\rho V^2} + \dfrac{C_{D_o} \frac{1}{2}\rho V^2}{W/A}} \qquad (D.4)$$

where:

- W = gross weight, in lbs
- D_T = total drag, in lbs
- A = lifting surface (wing) area, in sq ft
- a = lifting surface (wing) aspect ratio = span/chord
- ρ = mass density of fluid (air for airplanes, sea water for hydrofoils)
- V = vehicle velocity, in ft/sec
- C_{D_o} = profile drag coefficient.

The major difference between this equation and Eq. (D.3) for buoyantly supported craft is the existence of the first term in the denominator. This term is a reflection of the induced drag of dynamically supported vehicles which does not exist for buoyantly supported craft. As a result of this term, the lift-to-drag ratio of dynamically supported craft degrades as speed is decreased below the cruising speed, whereas for buoyantly supported craft, a decrease in speed always results in improved lift-to-drag ratio. This is evident in Figs. D.1, D.2, and D.3.

As the speed of hydrofoil craft is further decreased, they cease to have sufficient dynamic support from their foils and they become buoyantly supported by the hull. According to Figs. D.1, D.2, and D.3, which are based on bare hull thrust horsepower, the transition from buoyant support to dynamic foilborne support takes place at the speeds shown in Table D-3.

TABLE D-3. TRANSITION FROM BUOYANT SUPPORT TO FOILBORNE SUPPORT ACCORDING TO FIGS. D.1 THROUGH D.3

Gross Weight (Tons)	Type of Hull	Transition Speed (Knots)
100	Planing	22
100	Ordinary surface ship	29
100	Series 64	34
1,000	Planing	24
10,000	Planing	30

Equation (D.4) shows no evidence of a dependence of W/D_T on size, as long as the wing loading W/A is held constant. As discussed in Ref. D.1, the wing loading values for hydrofoil craft had an upper limit of about 1,400 lbs per sq ft imposed by cavitation considerations. This is the value used in this report (see Table D-4). With a fixed value of wing loading, Figs. D.1, D.2, and D.3 show the same specific power values for hydrofoil craft of 100 tons, 1,000 tons, or 10,000 tons.

Table D-4 describes the configuration of the hydrofoil craft used in this report. Note the very low C_V value of the hydrofoil craft hull assumed for the parent vehicle in order to achieve as low a take-off power as possible. In this table, the relation between size and weight given by Eq. (D.2) is used to determine the dimensions of the hydrofoil hull. However, Eq. (D.2) is not used to determine the wing area which is determined rather by the limiting value of W/A of 1,400 lbs/sq ft.

TABLE D-4. HYDROFOIL CONFIGURATION DATA

Characteristic	Weight, long tons 100	1,000	10,000
Length, water line ft	140	305	650
Beam, ft	23.8	51.4	110
Volumetric Coefficient, Underwater Volume at Rest/Length^3, C_V	0.00127	0.00127	0.00127
Profile Drag Coefficient	0.02	0.02	0.02
Wing Area, sq ft	160	1,600	16,000
Wing Loading, lbs/sq ft	1,400	1,400	1,400
Wing Aspect Ratio	3.0	3.0	3.0

Parent Vehicle	
Name	AGEH (Plainview)
Country	United States
Weight	318 tons
Length	206 ft
Beam	35 ft
Volumetric Coefficient	0.00127
Wing Loading	1,400 lbs/sq ft
Wing Aspect Ratio	3.0
Profile Drag Coefficient	0.02
Speed	45 knots

It is evident from Figs. D.4, D.5 and D.6 that hydrofoil craft show favorable values of P_t/W_v in relation to other craft only in small sizes and at modest speeds. Because of cavitation considerations, currently feasible hydrofoil craft are limited to speeds of 50 knots or less.

D.4 SPECIFIC POWER FOR PLANING CRAFT

Planing craft differ from other dynamically supported craft in several major respects. One obvious difference is that planing craft do not employ special lifting surfaces to develop the necessary hydrodynamic lift; rather, they rely on their hull bottoms to develop lift. A second, more subtle difference concerns take-off speed. All dynamically supported craft gradually change their mode of support as their speed increases from zero. However, the speed at which an airplane ceases to be groundborne and becomes completely airborne or a hydrofoil ceases to be hullborne and becomes completely foilborne, is readily observable and predictable with some precision in practice. Such is not the case with planing craft; the speed at which they cease to be buoyantly supported and become completely dynamically supported is neither readily observable nor predictable with precision. Based on empirical evidence, the approximate speed at which a planing craft becomes completely dynamically supported corresponds to a volume Froude number* of 3.5.

Because of the constraint on shape imposed by the necessity for the hull bottom to be the lifting surface, planing craft have very high drag while buoyantly supported. This is clearly evident from Figs. D.1, D.2, and D.3. While planing craft do have less drag than surface ships at high speeds, their performance in that speed range is poor in relation to all vehicle types, except surface ships.

Table D-5 gives complete data on the planing craft used in this report. Equation (D.2) was used to determine all linear dimensions,

---

*The volume Froude number is defined as $F_\nabla = V/\sqrt{g}\nabla^{1/3}$, where ∇ is the planing craft underwater volume when the craft is at rest. Since planing craft are buoyantly supported at zero and low speeds, $W = \rho g \nabla$ so that $F_\nabla = V/[(g/\rho)gW]^{1/6}$.

areas and volumes. As a result, the loading parameter W/A is not constant with vehicle weight as it was for hydrofoil craft but rather increases with increasing vehicle weight directly with the scale ratio determined by Eq. (D.2).

TABLE D-5. PLANING CRAFT CONFIGURATION DATA

Characteristic	Weight, long tons 100	1,000	10,000
Length, water line ft	78	168	362
Beam, ft	25.5	54.8	118
Volumetric Coefficient, Underwater Volume/Length^3, C_V	0.00736	0.00736	0.00736
Projected Total Bottom Area, A, sq ft	1,640	7,610	35,200
Loading Parameter, W/A, lbs/sq ft	137	294	637
Speed at $F_\nabla = 3.5$, knots	45.8	67.3	98.9

Parent Vehicle	
Name	--
Country	--
Reference	1963 S.N.A.M.E. Trans., p. 495, Model 4666; W.A.I.V., Table 7.3, Vehicle No. 2
Weight	318 tons
Length, water line	114.7 ft
Mean Beam	37.5 ft
Volumetric Coefficient, Volume/Length^3	0.00736
Projected Total Bottom Area	3,560 sq ft

D.5 SPECIFIC POWER FOR SEMI-PLANING SHIPS

This vehicle type is identified as a semi-planing ship not because it ever achieves complete dynamic support, but because it achieves the speeds associated with planing. This vehicle type was designed and tested at the Naval Ship Research and Development Center (NSRDC) and designated as the Series 64. The data source and particulars of these vehicles are included in Table D-6.

TABLE D-6. SEMI-PLANING SHIP CONFIGURATION DATA

Characteristic	Weight, long tons		
	100	1,000	10,000
Length, ft	171	368	794
Beam, ft	9.52	20.5	44.2
Draft, ft	4.76	10.25	22.1
Wetted Area, sq ft	2,030	9,922	43,718
Volumetric Coefficient, C_v	0.0007	0.0007	0.0007
Prismatic Coefficient, C_p	0.63	0.63	0.63
Maximum Section Coefficient	0.714	0.714	0.714
Speed at $F_n = 0.5$, knots	21.9	32.1	47.1
Speed at $F_\nabla = 3.5$, knots	45.8	67.3	98.9

Parent Vehicle	
Name	--
Country	United States
Reference	Marine Technology, July 1965, p. 248
Weight	--
Length	--
Volumetric Coefficient	0.000525 to 0.00192
Prismatic Coefficient	0.63
Beam/Draft Ratio	2, 3, and 4
Maximum Section Coefficient	0.556, 0.714, 0.873

The vehicle configuration whose P_t/W_v data are shown in Figs. D.1, D.2, and D.3 is very extreme. It has a volumetric coefficient of only 0.0007 (compared to 0.0017 for the surface ship discussed in Section D.2) a beam draft ratio of only 2, and a low maximum section coefficient of 0.714. As a result of its very low volumetric coefficient, it has a significantly larger wetted area than the surface ship described in Section D.2. This extreme configuration was selected not because it is a practical configuration but because it very likely represents the best possible performance at high speeds of a buoyantly supported vehicle. Its presence on Figs. D.1, D.2, and D.3 should not cause it to be regarded as a feasible alternative to the surface ship treated in those figures and described in Section D.2.

With these qualifications in mind, it should be observed in Figs. D.1, D.2, and D.3 that this configuration has considerably lower drag than a conventional surface ship at speeds greater than:

15 knots for 100 tons
20 knots for 1,000 tons
27 knots for 10,000 tons.

Its increased drag at lower speeds is caused partially by its increased wetted area.

The specific thrust power figures also indicate that of all the surface vehicles included on the figures, this configuration has the lowest drag of any of them at the following speeds and sizes:

Size, tons	Speed, knots
100	15 to 35
1,000	20 to 30
10,000	27 to 44

It is also of interest to note that in the 1,000-ton size (let alone the 10,000-ton size) this configuration has less drag than a hydrofoil craft at any speed.

D.6 SPECIFIC POWER FOR ACVs

The configuration used for the air cushion vehicles of this report is given in Table D-7. It should be noted that Eq. (D.2) is adhered to even though it is not mandatory for ACV craft. Thus, the cushion pressure of the parent vehicle (40 lbs/sq ft) is modified directly by the scale ratio determined by Eq. (D.2) for the 100-ton, 1,000-ton, and 10,000-ton ACVs.

TABLE D-7. ACV CONFIGURATION DATA

Characteristic	Weight, long tons 100		1,000		10,000	
Length/Beam Ratio	1.68		1.68		1.68	
Length, water line ft	108.2		232		502	
Beam, ft	65		138		298	
Cushion Area, S_c, sq ft	6,620		30,700		143,500	
Cushion Pressure, lbs/sq ft, W/S_c	33.8		72.8		156.3	
Cushion Pressure/Length, lbs/cu ft	0.313		0.313		0.313	
Vehicle Weight/Cushion Area$^{3/2}$, $W/S_c^{3/2}$, lbs/ft^3	0.415		0.415		0.415	
Vertical Clearance, in.	9.00	7.67	9.00	16.35	9.00	35.3
Cushion Area/Gap Area	26.8	31.6	57.6	31.6	124.0	31.6
Discharge Coefficient, D_c	0.60		0.60		0.60	
Air Profile Drag Coefficient, C_{D_o}	0.10		0.10		0.10	

Parent Vehicle

Name	SRN-4
Country	England
Weight, Normal	165 tons
Length	128 ft
Beam	76 ft
Cushion Pressure	40 lbs/sq ft
Cushion Pressure/Length	0.313 lbs/cu ft
Vertical Clearance	9 in.
Cushion Area/Gap Area	31.6
Speed	70 knots

The basic equation for the lift-to-drag ratio of ACV craft as given by Eq. 7.34 of Ref. D.1 is as follows:

$$\frac{W}{D_{T'}} = \frac{1}{\frac{S_g D_c}{V\, S_c}\left(\frac{W}{\frac{1}{2}\rho_a S_c}\right)^{\frac{1}{2}} + \frac{\frac{1}{2}\left(\rho_a C_{D_o} + \rho_w C_w\right)V^2}{W/S_c}} \qquad \text{(D.5)}$$

where

W = vehicle gross weight, lbs

$D_{T'}$ = equivalent total drag (including lift power), lbs

S_g = gap area, sq ft

D_c = discharge coefficient

V = vehicle velocity, ft/sec

S_c = cushion area, sq ft

ρ_a = mass density of air, lbs sec^2/ft^4

C_{D_o} = profile drag coefficient

ρ_w = mass density of sea water, lbs sec^2/ft^4

C_w = wave drag coefficient

The first term on the left of the denominator of Eq. (D.5) is the cushion power equivalent drag. The second term is the ordinary drag term which is similar to that of Eq. (D.3) for buoyantly supported vehicles or the second term of the denominator of Eq. (D.4) which is for dynamically supported vehicles.

Two sets of data for the ACVs are included in Figs. D.1 to D.6 of this report. One set of data is for a fixed vertical clearance of 9 in. (which is the clearance of the parent vehicle, the SRN-4) whereas the other set is for vertical clearances that vary with vehicle size and weight. The relation between vertical clearance and vehicle weight for the second set of data follows Eq. (D.2) starting with a clearance of 9 in. associated with a vehicle of 165 tons as given in Table D-7 for the SRN-4. Figures D.4, D.5, and D.6 show that the fixed clearance of 9 in. results in very favorable performance for the large ACVs at high speeds. However, an average clearance of 9 in. is very small on a craft 502 ft x 298 ft (see Table D-7), hence the larger clearances are probably more appropriate. Figures D.4, D.5, and D.6 show that allowing the clearance to increase directly with linear dimensions degrades performance significantly with increasing size for all vehicles between 100 and 10,000 tons at speeds of 40 or 50 knots. At 70 knots, the effect of increasing clearance, while detrimental compared to constant clearance, still allows the performance to improve with increasing size between 100 tons and 2,000 tons but degrades performance above that size.

Figures D.1 to D.3 show that the ACVs with the clearances increasing in size have the lowest power per ton of all other vehicle types considered at the following speeds and sizes:

Size, tons	Speed, knots
100	>38
1,000	>60
10,000	>85

D.7 SPECIFIC POWER FOR SESs

The Surface Effects Ship (SES) is an air-cushion vehicle whose sides penetrate the water surface. The sides thus seal off the air cushion, reducing leakage losses and reaching cushion power equivalent drag, while simultaneously introducing water frictional drag. The ends of the cushion are partially sealed off by devices that do not penetrate the water surface as the sides do, but essentially ride on the water surface following the wavy free surface.

The basic equation for the lift-to-drag ratio of SES craft is similar to Eq. (D.5) for the ACV, except for the addition of one term. The equation is as follows:

$$\frac{W}{D_{T'}} = \frac{1}{\frac{S_g D_c}{V\, S_c}\left(\frac{W}{\frac{1}{2}\rho_a S_c}\right)^{\frac{1}{2}} + \frac{\frac{1}{2}\left(\rho_a C_{D_o} S_c + \rho_w C_w S_c + \rho_w C_f S\right) V^2}{W}} \quad . \qquad \text{(D.6)}$$

The additional term is $\rho_w C_f S$ in the second term of the denominator which takes account of the water frictional drag of the sidewalls penetrating the water surface. In Eq. (D.6), S represents the wetted area of the sidewalls.

The general configuration of the SES craft described in the first paragraph of this section suggests that, unlike the ACV, a long, narrow SES craft may be attractive compared to a short, wide SES craft for some applications. As a result, the specific power figures of this report show P_t/W_v values for two length-to-beam (L/B) ratios, 2.3 and 6.5. Complete configuration data for these two SES craft appear in Table D-8. Three sets of different clearance values are used for each of the two L/D values. The first clearances, identified in the table as NSRDC, are very low clearances assumed in the NSRDC estimates of SES performance furnished for this study. These are the clearance values assumed in the specific power values for SES craft given in Figs. D.1, D.2, and D.3. To show the effect on SES performance of larger assumed clearances, the same clearance values assumed for the ACV calculations are used for the SES P_t/W_v data in Figs. D.4 to D.6 of Section D.1. The cushion-area/gap-area ratios resulting from these clearances are shown in Table D-8. In general, of course, the cushion-area/gap-area ratio is much larger for SES craft than for ACV craft (see Table D-7).

The P_t/W_v values for the two SES craft with different L/B ratios in Figs. D.1, D.2, and D.3 show a very important result. The longer, narrower craft is much more favorable at low speeds and less favorable at high speeds. The first result follows from the first term of the denominator of Eq. (D.6) because of the lower gap-area/cushion-area ratio of the long, narrow craft relative to the shorter, wider craft. This term dominates at low speeds. The first result also

TABLE D-8. SES CONFIGURATION DATA

Characteristic	Weight, long tons 100	1,000	10,000
Vehicle Weight/Cushion Area$^{3/2}$, $W/S_c^{3/2}$, lbs/cu ft	2.0	2.0	2.0
Cushion Pressure, W/S_c, lbs/sq ft	96.7	203.5	448
Cushion Area, S_c, sq ft	2,320	11,000	50,000
Low L/B:			
Length/Beam Ratio	2.3	2.3	2.3
Length ft, L	72.8	157	338
Beam, ft, B	31.6	68.3	147
Vertical Clearances, NSRDC, in., h	3.25	4.22	5.73
Gap Area, S_g, sq ft = 2 Bh	17.2	48	141
Cushion Area/Gap Area, S_c/S_g	129	229	355
Vertical Clearances, h, in.	9	9	9
Gap Area, S_g, sq ft	47.5	102.5	221
Cushion Area/Gap Area S_c/S_g	46.9	107.5	226
Vertical Clearances, h, in.	7.67	16.35	35.3
Gap Area, S_g, sq ft	40.3	186	865
Cushion Area/Gap Area, S_c/S_g	58	58	58
High L/B:			
Length/Beam Ratio	6.5	6.5	6.5
Length, L, ft	123	264	570
Beam, B, ft	18.9	40.6	86.1
Vertical Clearances, NSRDC, h, in.	2.9	3.26	4.7
Cushion Area/Gap Area, S_c/S_g	254	497	741
Vertical Clearance, h, in.	9	9	9
Cushion Area/Gap Area, S_c/S_g	81.8	180	387
Vertical Clearances, h, in.	7.67	16.35	35.3
Cushion Area/Gap Area S_c/S_g	98	98	98

follows from the much larger wave drag at low speed of the wide, short SES. The second result follows from the second term of the denominator of Eq. (D.6), which dominates at high speed. In this term, the larger wetted area of the high L/B SES penalizes it relative to the low L/B configuration.

Compared to other surface vehicles, Figs. D.1, D.2, and D.3 show that the high L/B SES craft compares favorably with all other surface craft (excluding the ACVs with 9-in. clearance in the 1,000- to 10,000-ton size range) in the speed range of 30 to 52 knots in the 1,000-ton size and in the speed range of 45 to 85 knots in the 10,000-ton size range.

Figures D.4 to D.6 show the unfavorable result of increased clearance on SES performance. The very favorable position of the high L/B SES at 40 knots in sizes above about 200 tons is shown in Fig. D.4 and at 50 knots (Fig. D.5) in sizes above 2,000 tons. At 70 knots (Fig. D.6), the low L/B SES is preferable to the high L/B configuration, except at sizes greater than 4,500 tons.

REFERENCE

D.1 Philip Mandel, Water, Air and Interface Vehicles, MIT Press, 1969.

APPENDIX E

POWER AND ACCELERATION OF TRACKED AND WHEELED VEHICLES ON A LOOSE GROUND

M.G. Bekker

CONTENTS

APPENDIX E

POWER AND ACCELERATION OF TRACKED AND WHEELED VEHICLES ON A LOOSE GROUND

E.1 OBJECTIVE

The tendency toward increasing engine power meets a limitation in ground capability of absorbing such power imparted by tracks and wheels, without excessive slip. The objective of this paper is to establish approximate values of such limitation, at least in one loose ground, for a heavy- and medium-tracked vehicle, and for a heavy-wheeled vehicle. To this end, level loose dry sand was selected as the environment of locomotion for M103A1 Tank (GVW = 125,000 lbs), the M113 Troop Carrier (GVW = 22,615 lbs), and for the "Goer" (GVW = 40,780 lbs).

In addition, in order to facilitate eventual similar evaluations for other soil types, computations of drag/weight ratio were performed for

- Moist agricultural soil (sandy loam)
- Wet, muddy soil
- Concrete.

E.2 METHOD

To achieve the objective, the drag/weight ratio (D/W) of a tracked vehicle was assumed to be defined by equation:

$$\frac{D}{W} = \frac{a}{g}\left[1 + \frac{g}{W}\sum\frac{I\eta\, i_t}{r^2}\right] + \frac{2bp^{(n+1)/n}\cos\beta}{W(n+1)[(k_c/b) + k_\phi]^{1/n}} + \sin\beta + \frac{D_i}{W} \quad , \text{(E.1)}$$

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where

W = gross vehicle weight, GVW (lb)

a = acceleration (ft/sec^2)

g = gravity acceleration (ft/sec^2)

$\delta = \left[1 + \frac{g}{W}\sum \frac{I\eta\, i_t}{r^2}\right]$ = factor due to the inertia of rotating masses. Following Gruzdev's treatise on tank design (1944), the factor is approximately 1 + 0.3 for heavy tanks, ~1 + 0.15 for medium tanks and ~1 + 0.08 for wheeled vehicles.

b = track width (in.)

p = ground pressure, nominal (psi)

β = angle of slope

n, k_c, k_ϕ = soil parameters

D_i = internal motion resistance due to friction between tracks, wheels, sprockets, idlers, etc. (lb), assumed to be $D_i/W = 0.05$.

The drag/weight ratio for wheeled vehicle may become very involved if the pneumatic tire behaves sometimes like a rigid wheel and sometimes like an elastic wheel. However, in the case considered here, the tires of the Goer in sand act as elastic wheels* and may be analyzed by means of the following equations:

$$\frac{D}{W'} = \frac{a}{g}[1+0.08] \tilde{+} \frac{D_s}{W'}\cos\beta + \sin\beta + \frac{D_t}{W'} \qquad \text{(E.2)}$$

*They may become rigid wheels in mud, which was not considered here.

where

D_s = tire motion resistance due to soil compaction (lb)

D_t = tire motion resistance due to the flexing of tire carcass.

Computation of D_s and D_t was performed, for the elastic wheel, using the following equations:

The resistance due to flexing the tire carcass is:

$$\frac{D_t}{W'} = \frac{\frac{d}{2} - \sqrt{\left(\frac{d}{2}\right)^2 - \left(\frac{\ell_1}{2}\right)^2}}{\ell_1} \quad . \tag{E.3}$$

The resistance due to soil compaction is:

$$\frac{D_s}{W'} = \frac{[b(P_i+P_c)]^{(n+1)/n}}{[k_c + bk_\phi]^{1/n}\ W} \tag{E.4}$$

where

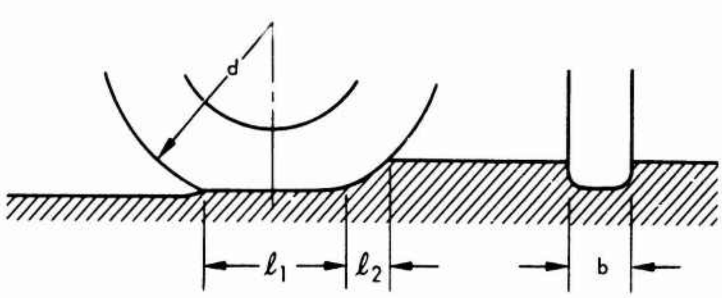
W' = wheel load (lb)

P_i = inflation pressure (psi)

P_c = carcass stiffness pressure (psi)

d = tire diameter (in.)

and,



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$$\ell_1 = \frac{W}{b(P_i + P_c)} - F\ell_2$$

$$\ell_2 = \frac{B - \sqrt{B^2 - 4AC}}{2A}$$

where

$A = b(P_i + P_c)[F^2/2 - K]$

$F = 1/(n+1)$

$K = 1/(n+1)(n+2)$

$B = WF/2$

$z_e = [P_i + P_c]/[(k_c/b) + k_\phi]^{1/n}$

$G = b\ z_e(P_i + P_c)/(n+1)$

$J = (D/2) - (z_e/3)$

$C = GJ$

P_c was assumed to be 6 psi. Other values are as defined before. The drag/weight ratios defined by Eqs. (E.1) and (E.2) comprise all the resistances that have to be overcome by the engine, except the air drag which has been neglected, as the speeds considered here were below 40 mph. The resistances are referred to sprocket radius r, and are balanced by soil thrust T which provides the ground reaction that drives the vehicle. Obviously, soil thrust T is not affected by internal motion resistances D_i and D_t of the vehicle. Thus, when balancing the drag/weight, D/W, of the vehicle with thrust/load of soil, T_s/W, the values of D_i and D_t should be dropped. This procedure, however, was not followed and forces D_i and D_t were not left out. This produced a more conservative solution since it counterbalanced the shift of the vehicles' CG, which occurs in dynamic conditions, and was not accounted for here.

The thrust/load, T_s/W, depends on the amount of slip, i_o, for both the tracks and the low-pressure pneumatic tires, as shown in the equation:

$$\frac{T_s}{W} = \left(\frac{c}{p} + \tan\phi\right)\left[1 - \frac{K}{i_o \ell}\left(1 - e^{-i_o \ell / K}\right)\right] \qquad \text{(E.5)}$$

where

c = coefficient of soil cohesion (psi)

ϕ = angle of soil friction (^{o})

K = coefficient of slip (in.)

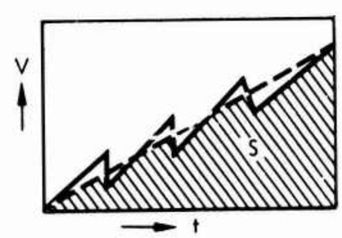
i_o = slip: $1 - (V_{actual}/V_{theoret})$

ℓ = length of the ground contact area (in.).

In motion: $D/W = T_s/W$, at the required slip, i_o.

Acceleration and the power required for that purpose are considered as measures of "mobility," since they directly relate to the top speeds attainable on level ground or slopes. In addition, acceleration is a measure of "agility" which appears to be a predominant justification of high-powered tank development. Such tanks are thought to be able to reduce the probability of a hit by a quick maneuver. This may be true to some extent, and deserves a most careful examination. However, providing greater hp/ton to get greater acceleration has no meaning without considering the forces T_s/W that can be absorbed by the ground at the given slip, i_o. It is thus worthwhile to consider the power required for acceleration under given slip conditions, at the assumed speed V_m that is expected to be achieved with acceleration a/g.

In general, the proving-ground measurements display increase of speed V as a function of time t, in the following form:



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where the acceleration distance S is $S = \int_0^t V\,dt$. Assuming the triangular V(t) function, in lieu of a zig-zag line following the changes of gears in the transmission, we have

$$V_m = at, \text{ and } \quad S = at^2/2 \quad ,$$

and the power needed to accelerate from zero to V_m in time t is

$$P = \frac{W}{g}\,\frac{aS}{t} \quad .$$

If the overall transmission efficiency is η_x and a/g is a function of i_o as limited by ground thrust T_s, then

$$\frac{P}{W} = \frac{a}{g}\,\frac{at^2}{2t\,\eta_x\,(1 - i_o)} = \frac{a}{g}\,\frac{V_m}{2\eta_x\,(1 - i_o)} \quad ,$$

or,

$$\frac{P}{W} = \frac{a}{g} \cdot \frac{V_m \times 2200}{2\eta_x \times \;550\;(1 - i_o)} = \frac{2.0}{\eta_x}\left(\frac{a}{g}\right)\frac{V_m}{1 - i_o} \quad , \qquad \text{(E.6)}$$

where P is in hp, W in tons and V in fps, and (a/g) is determined for the given i_o. Then P/W is the power required to achieve speed V_m, under given slip conditions and acceleration in the given soil. With no acceleration requirement, the vehicle can obviously achieve speeds higher than V_m. However, this is considered of little interest at this stage of the study since the maximum speed of any vehicle is limited, for practical purposes, not by the lack of power but by the roughness of the terrain surface, which induces discomfort, structural overloads, and directional instability.

E.3 SOIL PROPERTIES

Equation (E.1) was computed for the following soil properties, assumed to be representative of important terrain environments:

DRY SAND (Desert): $k_c = 0$ $k_\phi = 12$ $n = 0.8$ $c = 0$ $\phi = 37^o$ $K = 1$

MOIST AGRICULTURAL SOIL: $k_c = 3.5$ $k_\phi = 5.0$ $n = 0.7265$ $c = 0.2$ $\phi = 20^o$ $K \cong 1$

MUDDY GROUND: $k_c = 2.0$ $k_\phi = 4.0$ $n = 0.3250$ $c = 0.4$ $\phi = 15^o$ $K \cong 1$

CONCRETE: $\mu = 0.70$ (steel-concrete)

Only the M113 and M103A1 were computed for D/W, T_s/W ratios in all the above soils and the acceleration power, hp/ton, was computed only for sand. The "Goer" computations were performed in sand only. Sand may be considered as a most "universal" and "uniform" medium since it changes very little in nature, and yet represents well most of the dry frictional granular soils. It might be interesting to consider also clayey, nonfrictional soils, in a plastic state. This, however, would be a nongeneral type of a comparison platform, and the wheeled vehicles would have to be excluded as they usually are inoperative in wet, clayey ground. For this reason, the Goer was not analyzed in muddy ground specified above. "Goer" also was considered as an all-axle-driven vehicle, since it would be unfair to compare a 2X4 vehicle with tracked vehicles, in off-road conditions.

E.4 COMPUTATIONS

Figure E.1 shows D/W versus acceleration on various slopes for the M103A1. Also T_s/W was plotted for slips in sand. This figure shows that for $\beta = 25^o$ the attainable acceleration at 5 percent slip is 0.15 g, and 0.21 g at slips of 60 percent or more. Figure E.2 shows the same in the agricultural soil. Note that the capacity of the soil to absorb the thrust force is much lower since the ground is not as strong as dry sand. This figure shows that the M103A1 cannot

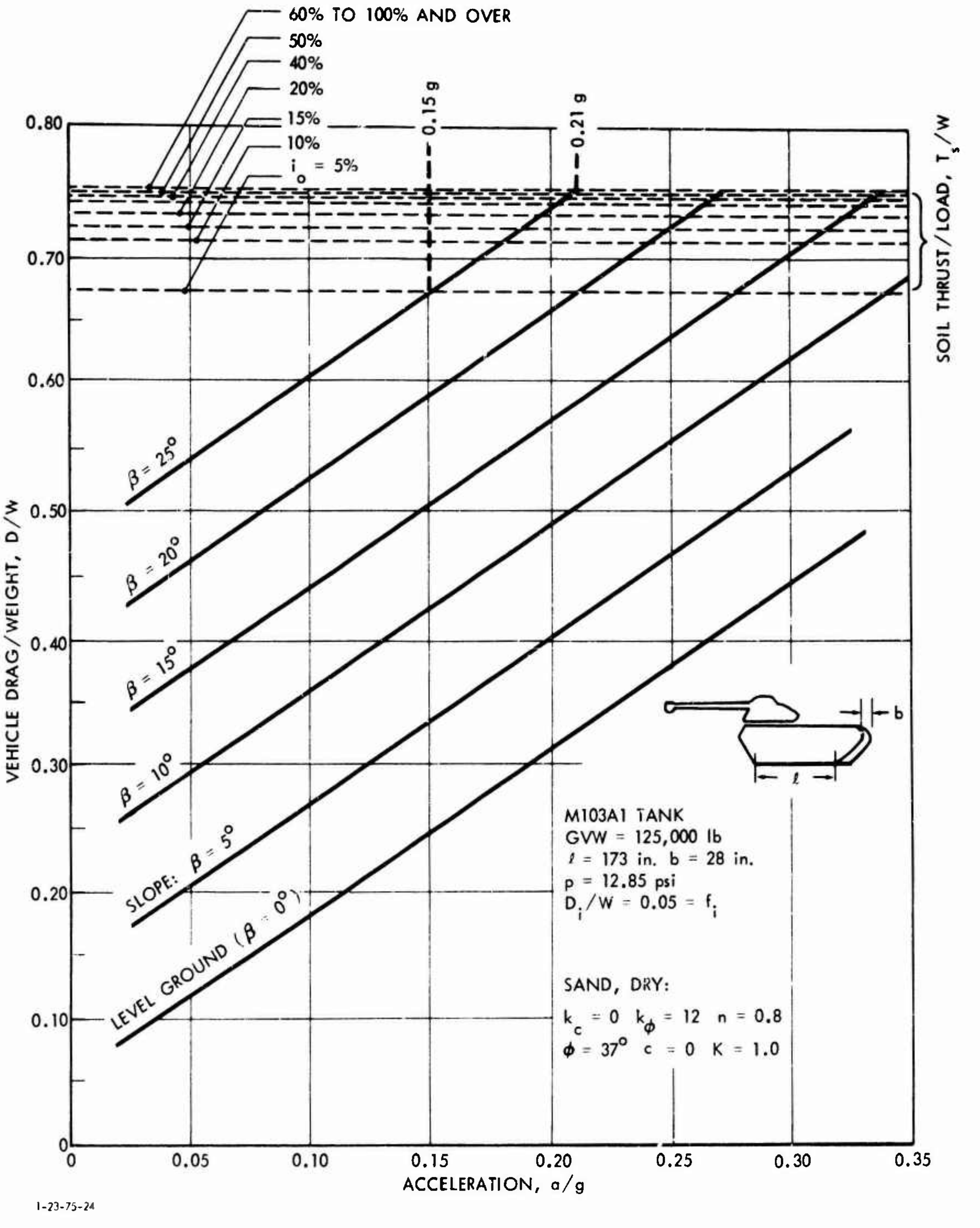

FIGURE E-1. Drag/Weight Ratios of a Heavy Tank at Various Accelerations, a/g, and Terrain Slopes, β, Versus Thrust-Load Ratios Available in Agricultural Soil at Various Slips, i_o

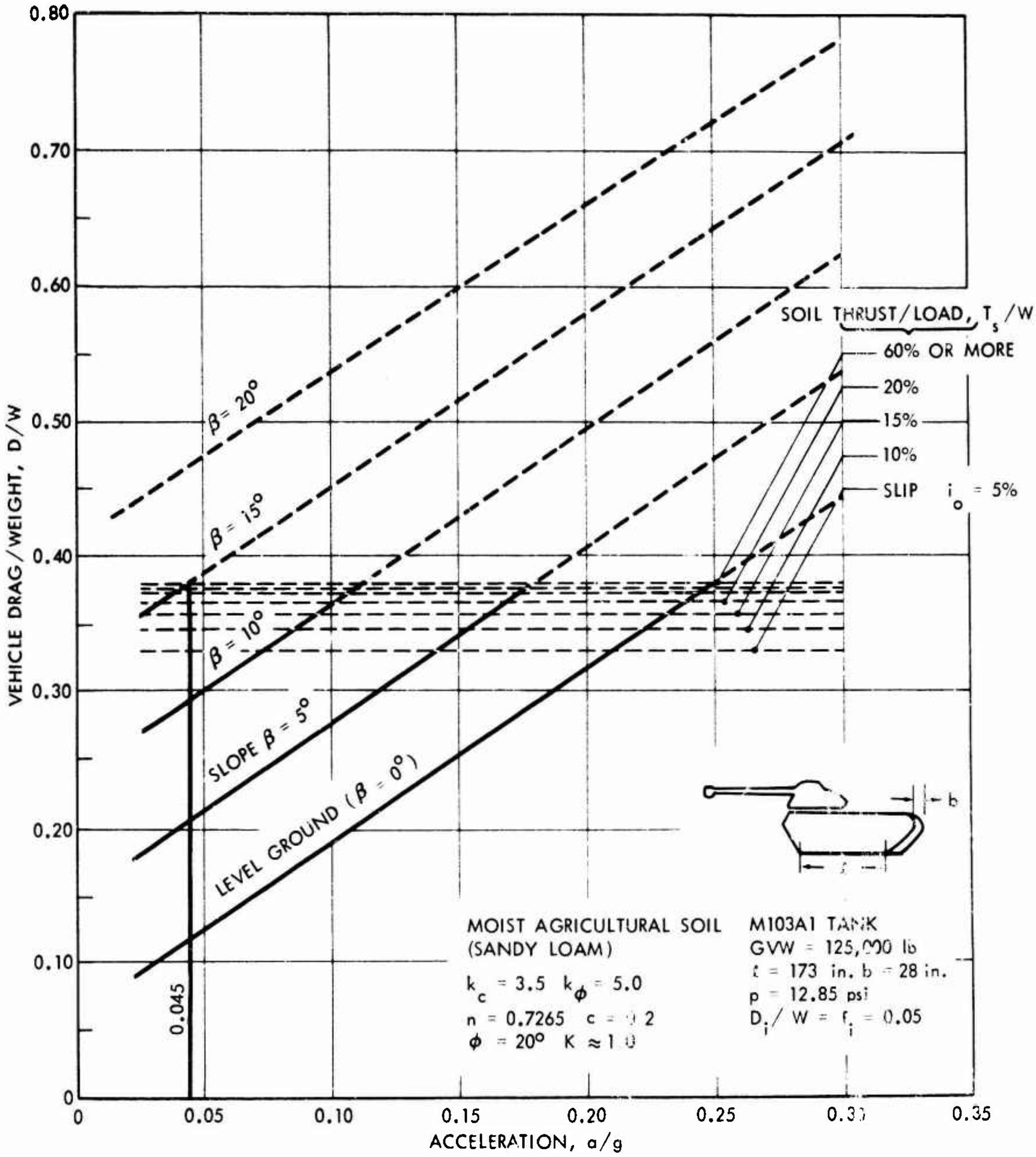

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FIGURE E-2. Drag/Weight Ratios of a Heavy Tank at Various Accelerations, a/g, and Terrain Slopes, β, Versus Thrust-Load Ratios Available in Agricultural Soil at Various Slips, i_o

climb a 15° slope, unless the acceleration is less than 0.045 g. By inference, the 20° slope is practically nonnegotiable. Figure E.3 illustrates the same phenomena in a much weaker ground, the muddy soil. Here, only level ground is negotiable with accelerations ~0.085 g at slips of 60 percent or more. Muddy soil thus almost completely inhibits agility regardless of D/W values. Figure E.4 repeats the computations for concrete. As the slip T_s/W lines converge very strongly, only one line for coefficient of friction $\mu = 0.7$ was drawn. All the soil values k_c, k_ϕ, and n are here nonexistent in the usual sense. Climbing abilities of the vehicle are limited only by $\mu = 0.7$ or 34.99° slope. Figure E.5 is similar to Fig. E.1. Only one T_s/W line for maximum slip-pull was shown for the M113. Figures E.6, E.7, and E.8 for the M113 display the great similarity between M113 and M103A1 in the soil conditions considered here. This is shown further in Fig. E.9 by the cross plots of a/g vs. β for the maximum attainable $D/W = T_s/W$, which is 0.75 for dry sand and 0.385 for agricultural soils. Note the rather insignificant differences between the 125,000-lb and 22,615-lb vehicles in spite of their different ground pressures: 12.85 and 7.3 psi. The reason for this is that the dominant terms in the D/W equation are the (hill climbing + acceleration) terms under the conditions computed.

Figure E.10 shows the accelerations that can be developed by the M103A1 at particular slip values, in sand and on level ground. Slips vs. $D/W = T_s/W$ are shown in Fig. E.11. On the same figure a slope of 5° was also considered to show the reduction in usable thrust/load values, with slope. Using Eq. (E.6) and assuming "terminal" speeds of 40, 20, 10, and 5 mph, graph Fig. E.12 was computed for the M103A1, for level ground only. On slopes, the graph lines would be shifted to the left. Figure E.13 shows again accelerations that can be developed by the ground vs. corresponding $D/W = T_s/W$ ratios at pertinent slips for the M113 in dry level sand. Figure E.14 gives the power requirements for target speeds of 40, 20, 10, and 5 mph that may materialize at accelerations available in ground thrust, at pertinent slips. Figures E.15 and E.16 produce similar data for the Goer, computed

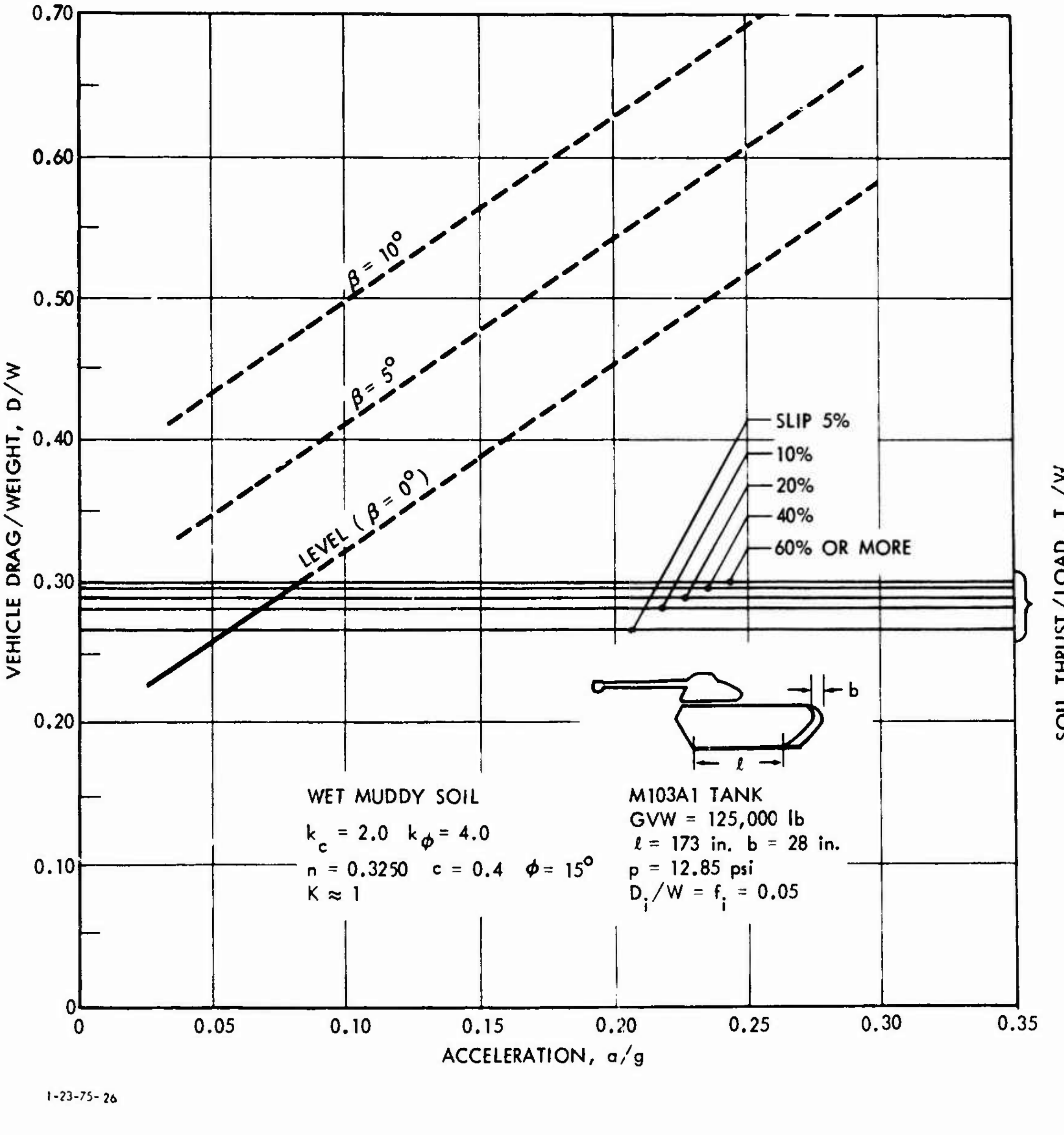

FIGURE E-3. Drag/Weight Ratios of a Heavy Tank at Various Accelerations, a/g, and Terrain Slopes, β, Versus Thrust-Load Ratios Available in the Ground at Various Slips, i_o

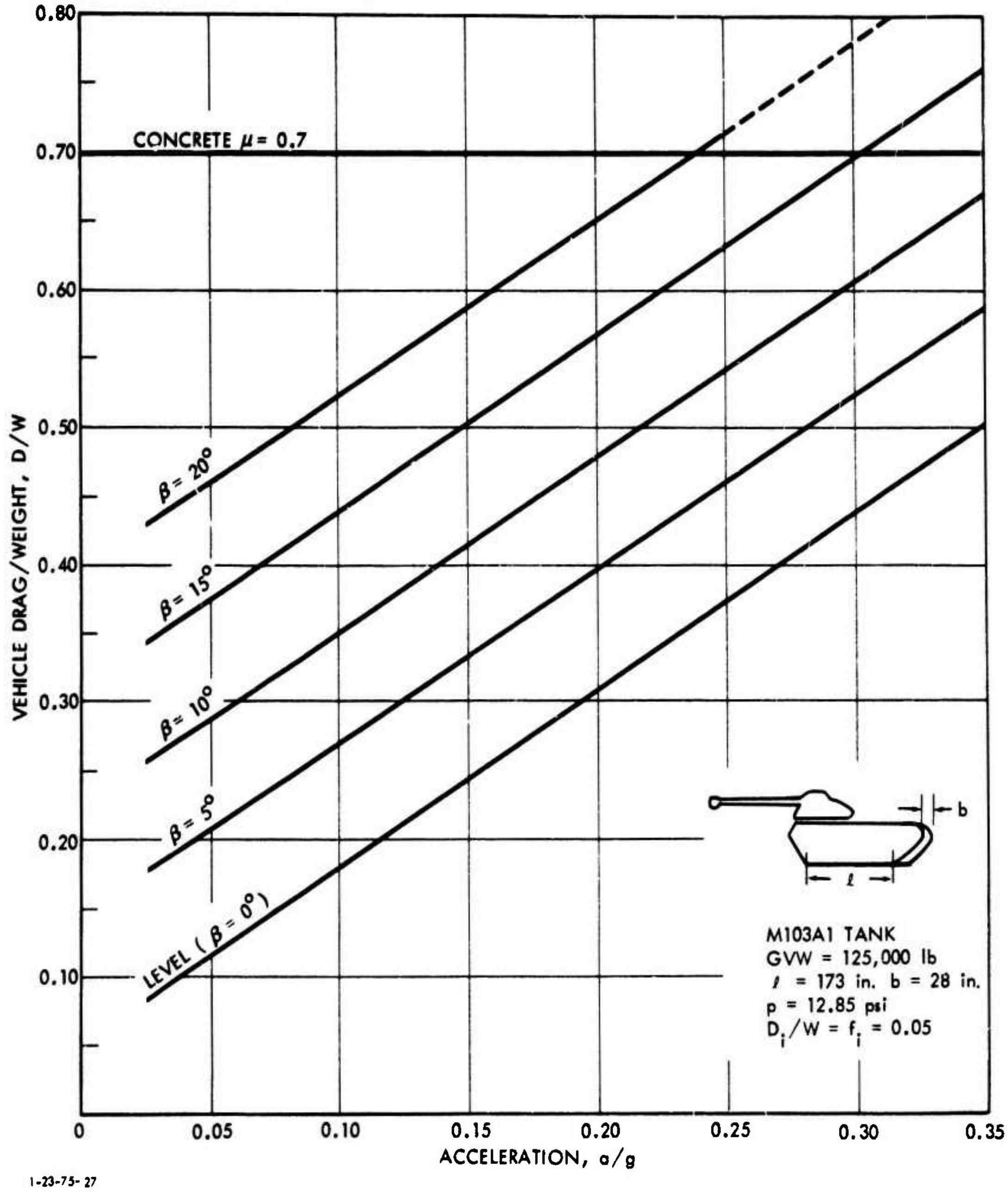

FIGURE E-4. Drag/Weight Ratios of a Heavy Tank at Various Accelerations, a/g, and Slopes, β, Versus Thrust-Load Available on Concrete

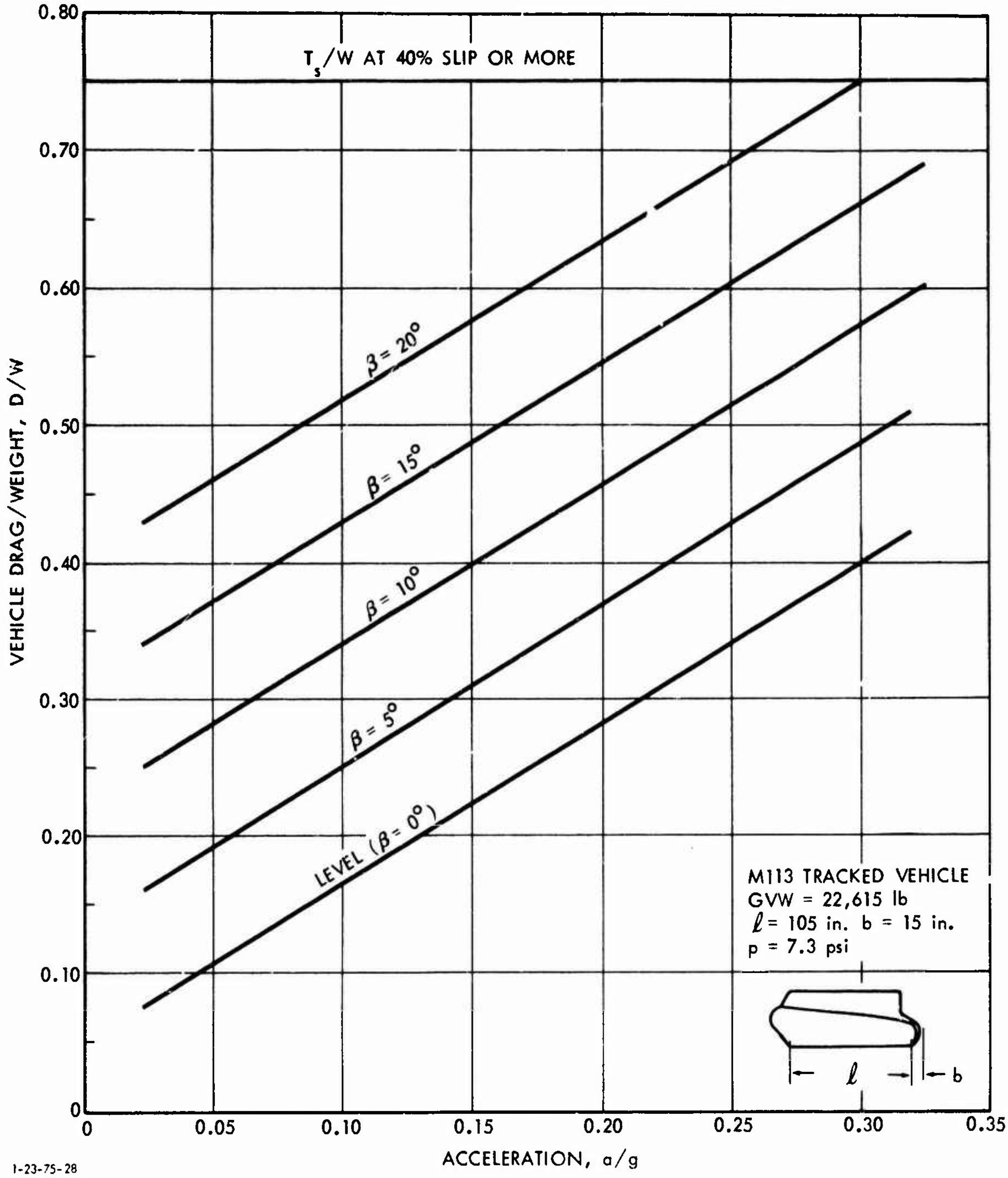

FIGURE E-5. Drag/Weight Ratios for a Tracked APC in Dry Sand

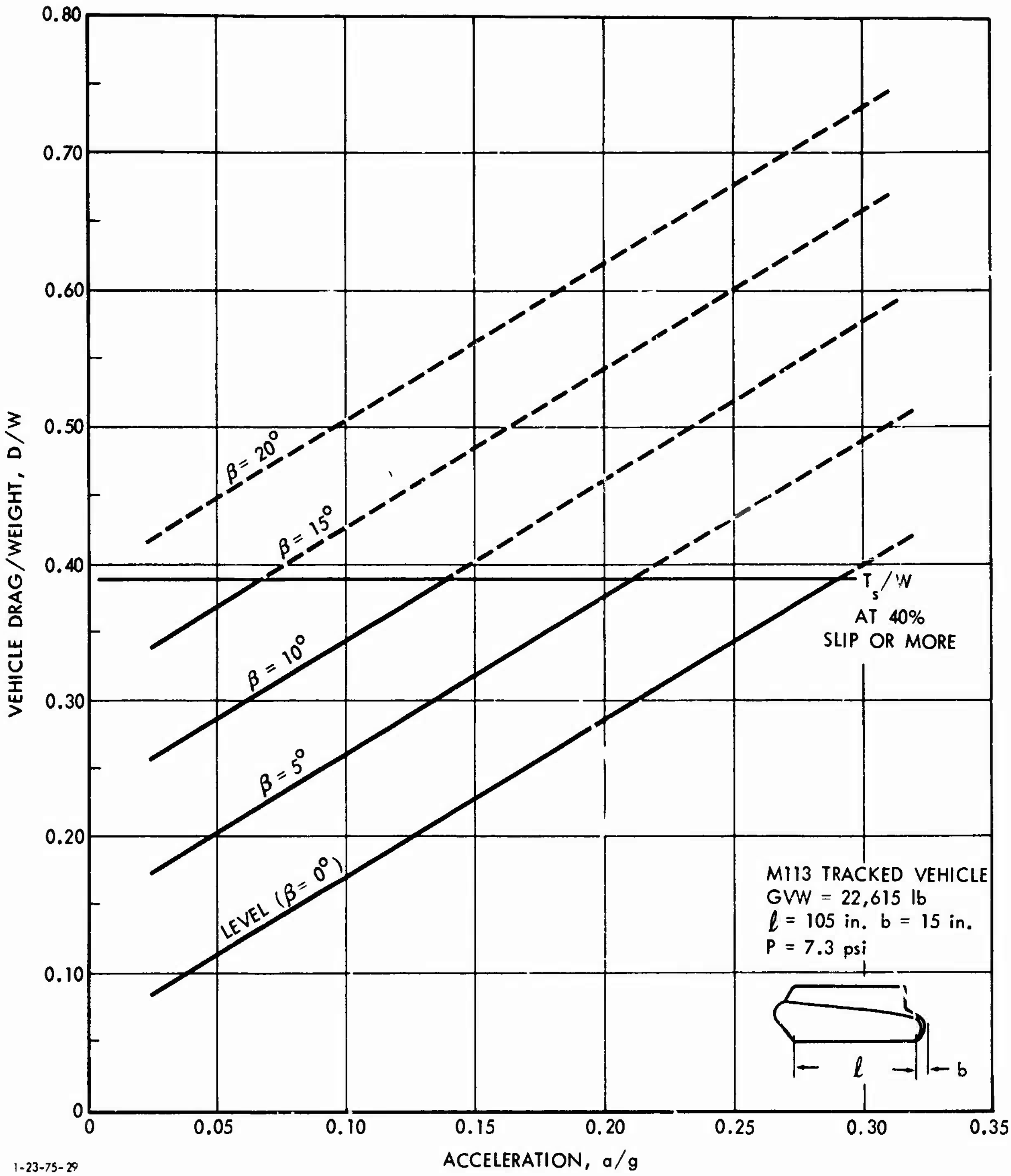

FIGURE E-6. Drag/Weight Ratios for a Tracked APC in Moist Agricultural Soil

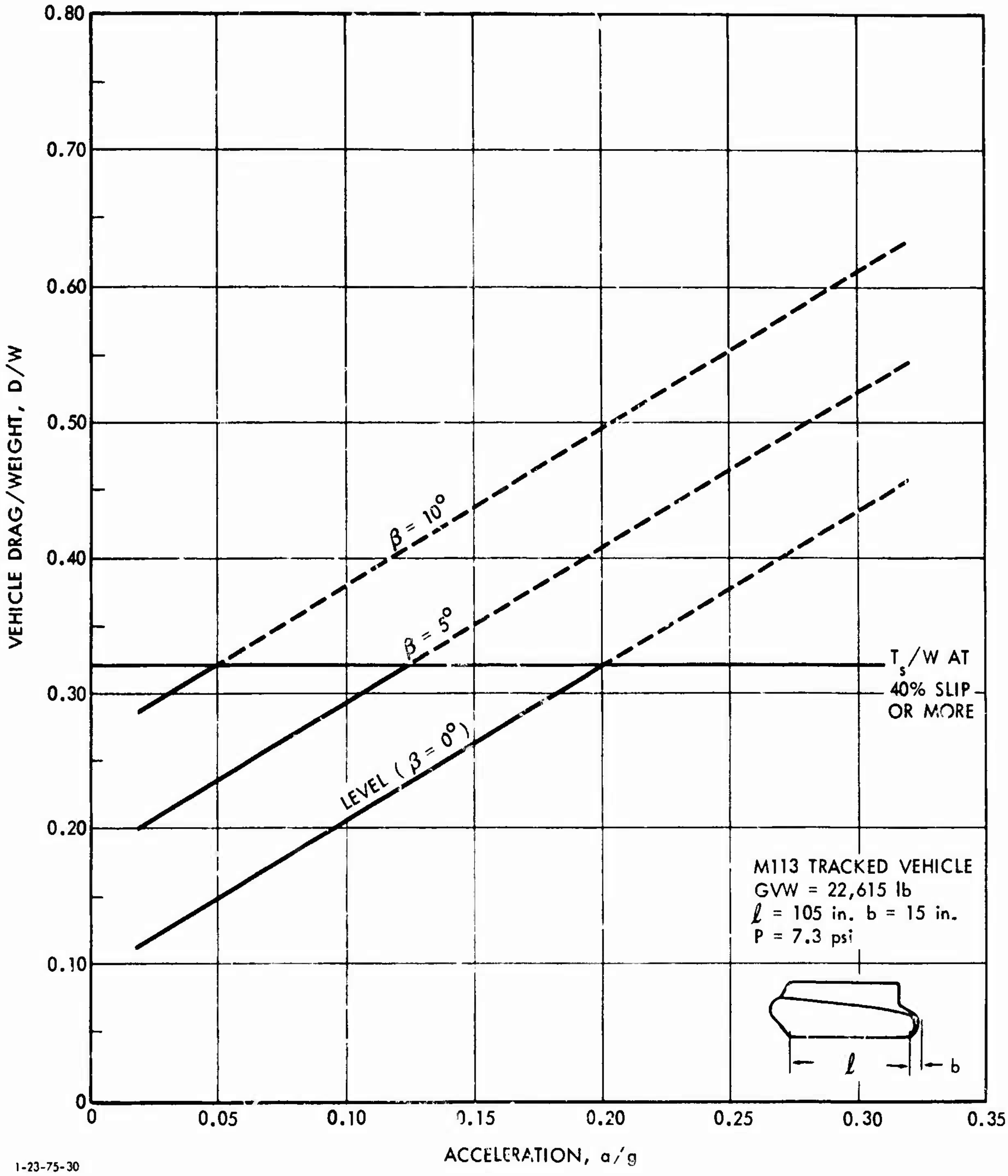

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FIGURE E-7. Drag/Weight Ratios for a Tracked APC in Muddy Wet Soil

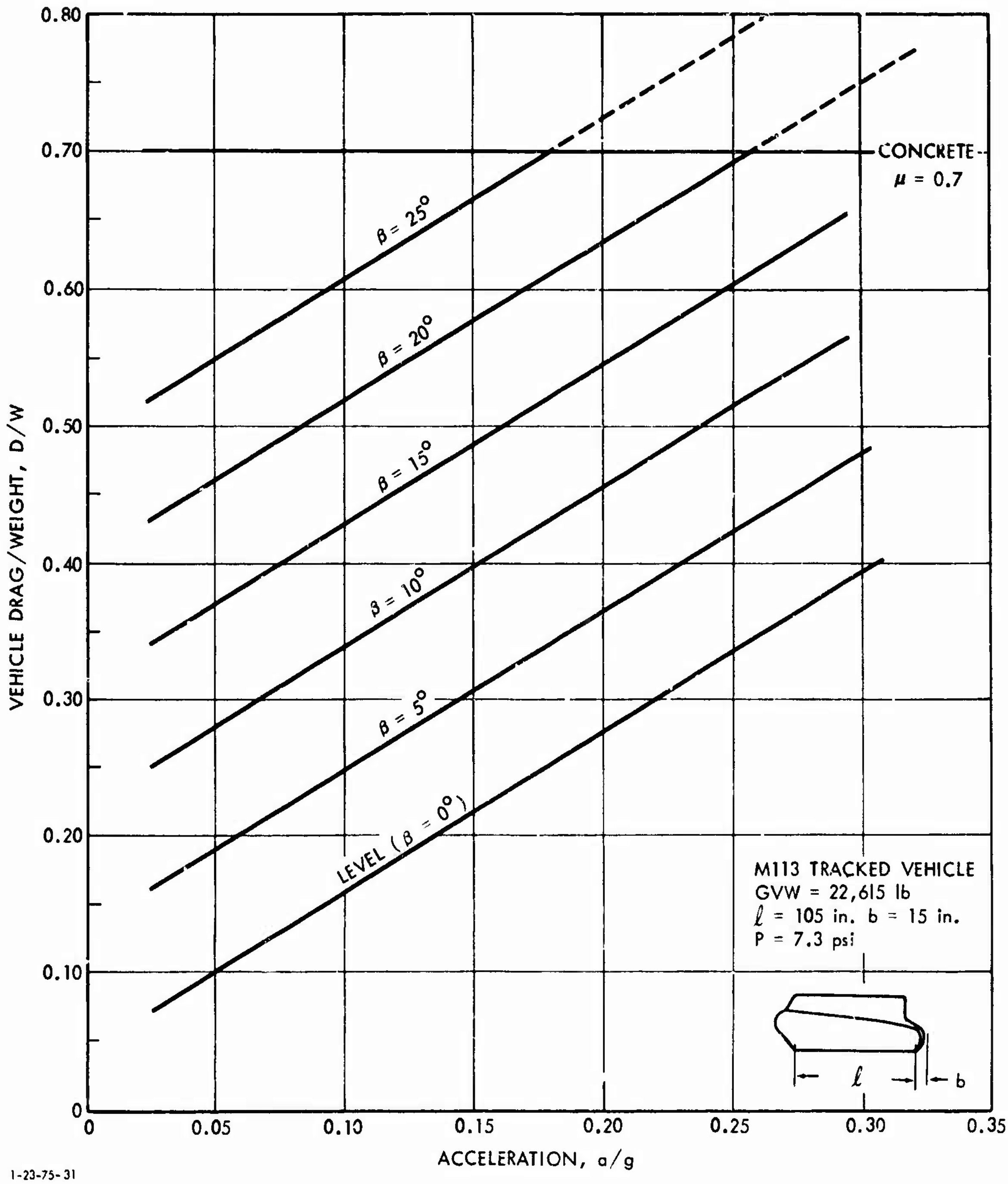

FIGURE E-8. Drag/Weight Ratios for a Tracked APC on Concrete

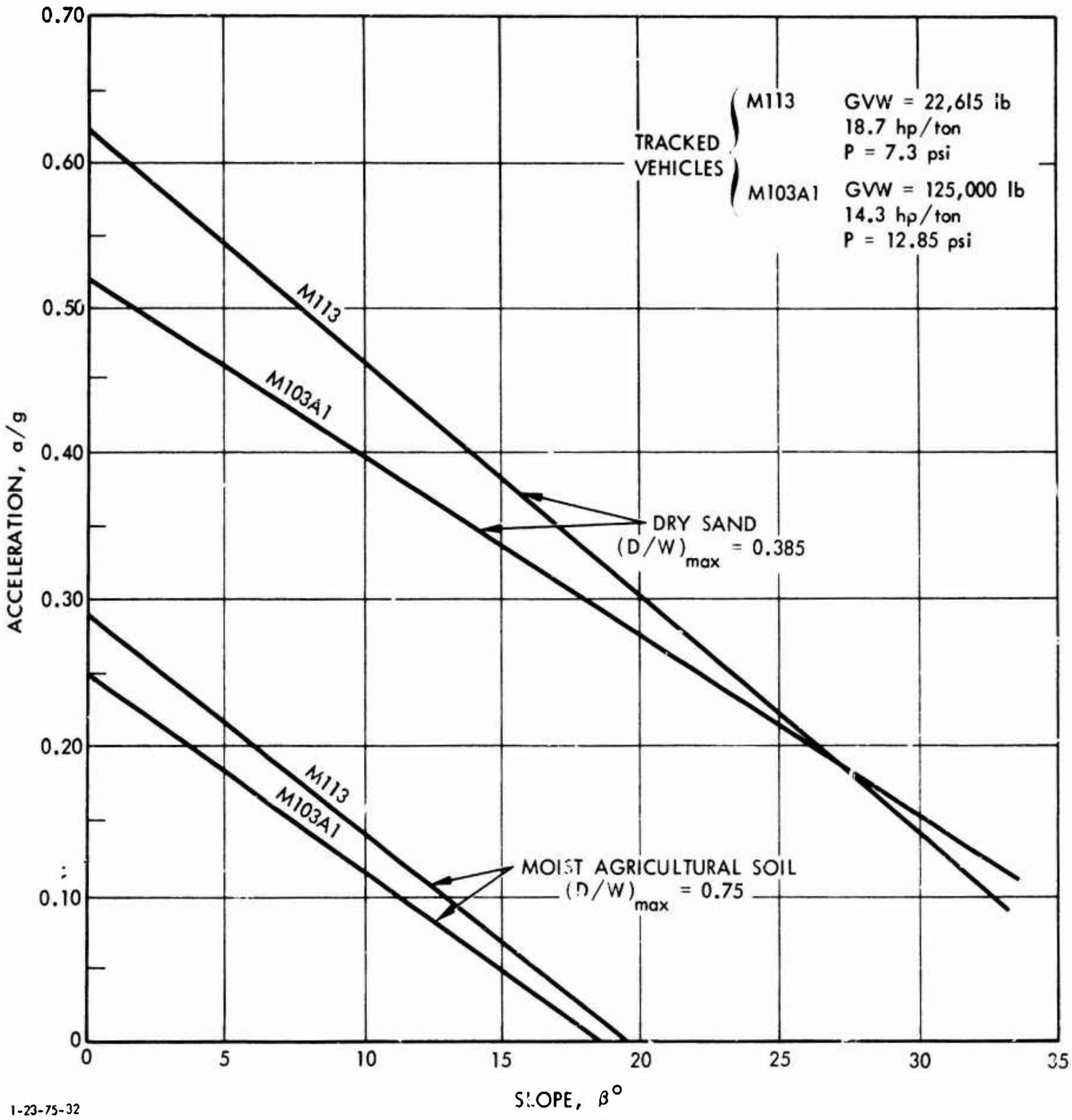

FIGURE E-9. Approximate Acceleration, a/g, Attainable at Various Slopes, in Dry Sand, and in an Agricultural Soil, at Maximum D/W, Limited by Track-Soil Adhesion

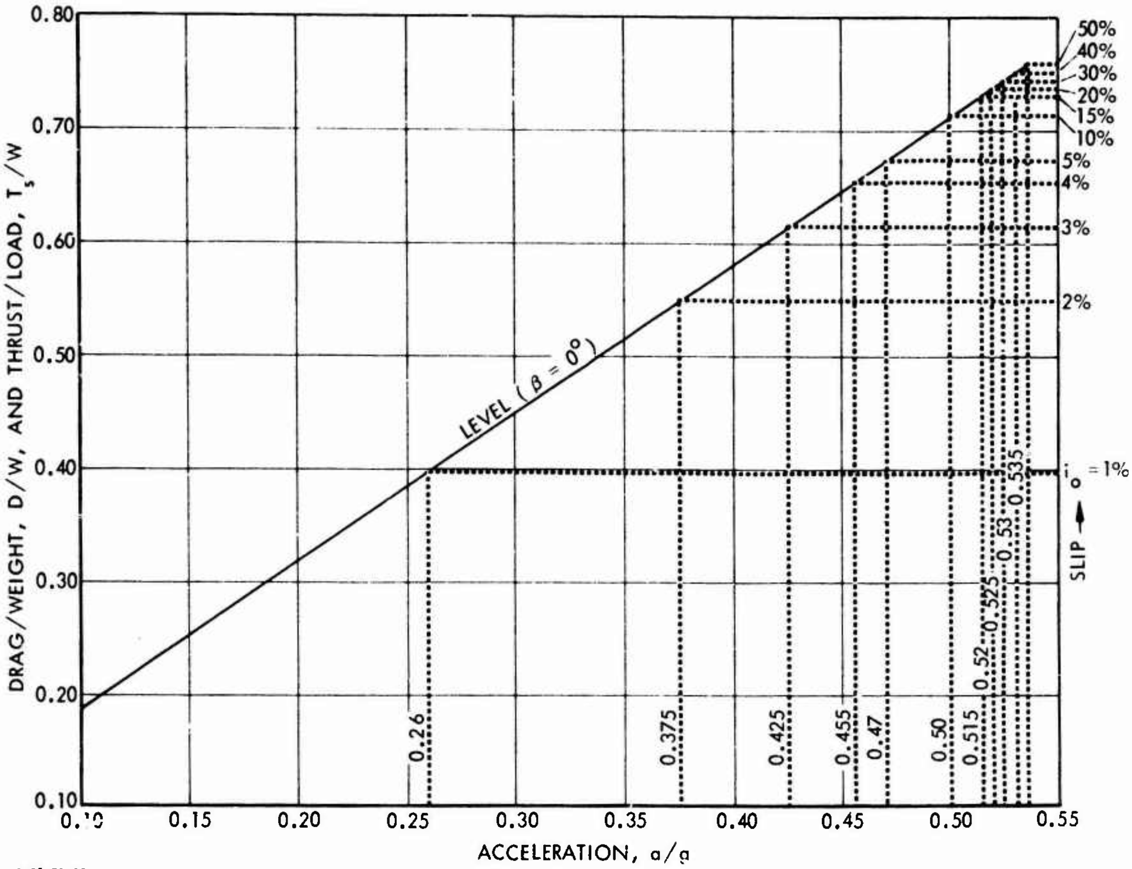

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FIGURE E-10. Performance of M103A1 Tank in Level, Dry Sand

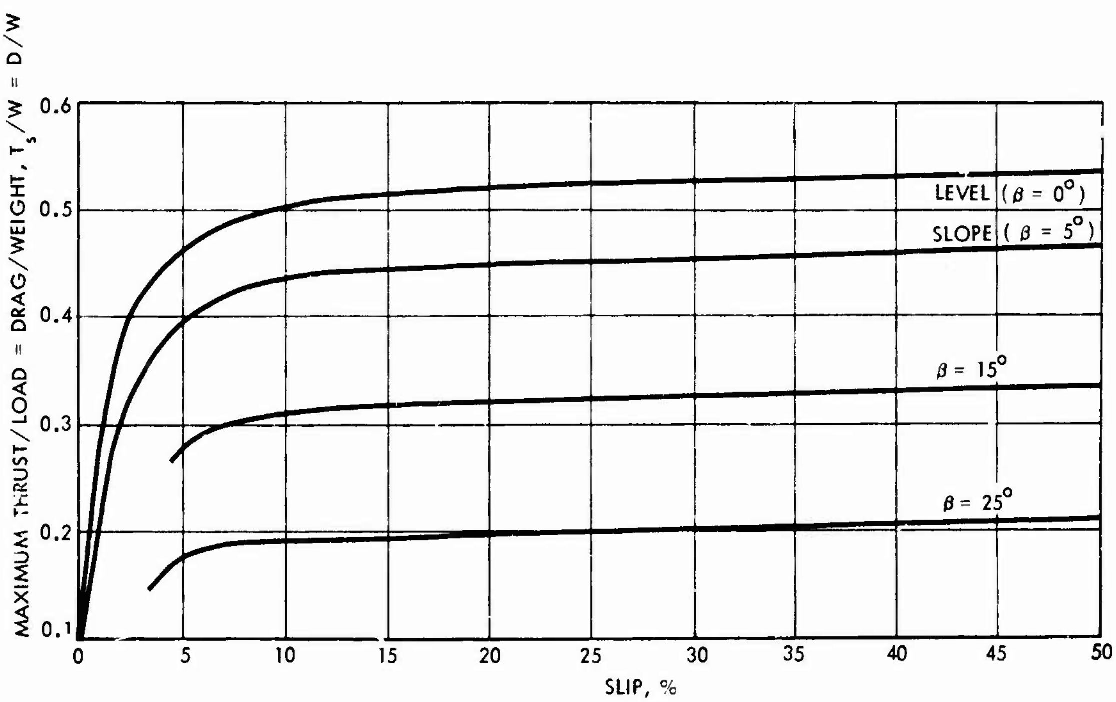

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FIGURE E-11. Performance of M103A1 Tank in Dry Sand at Different Slopes

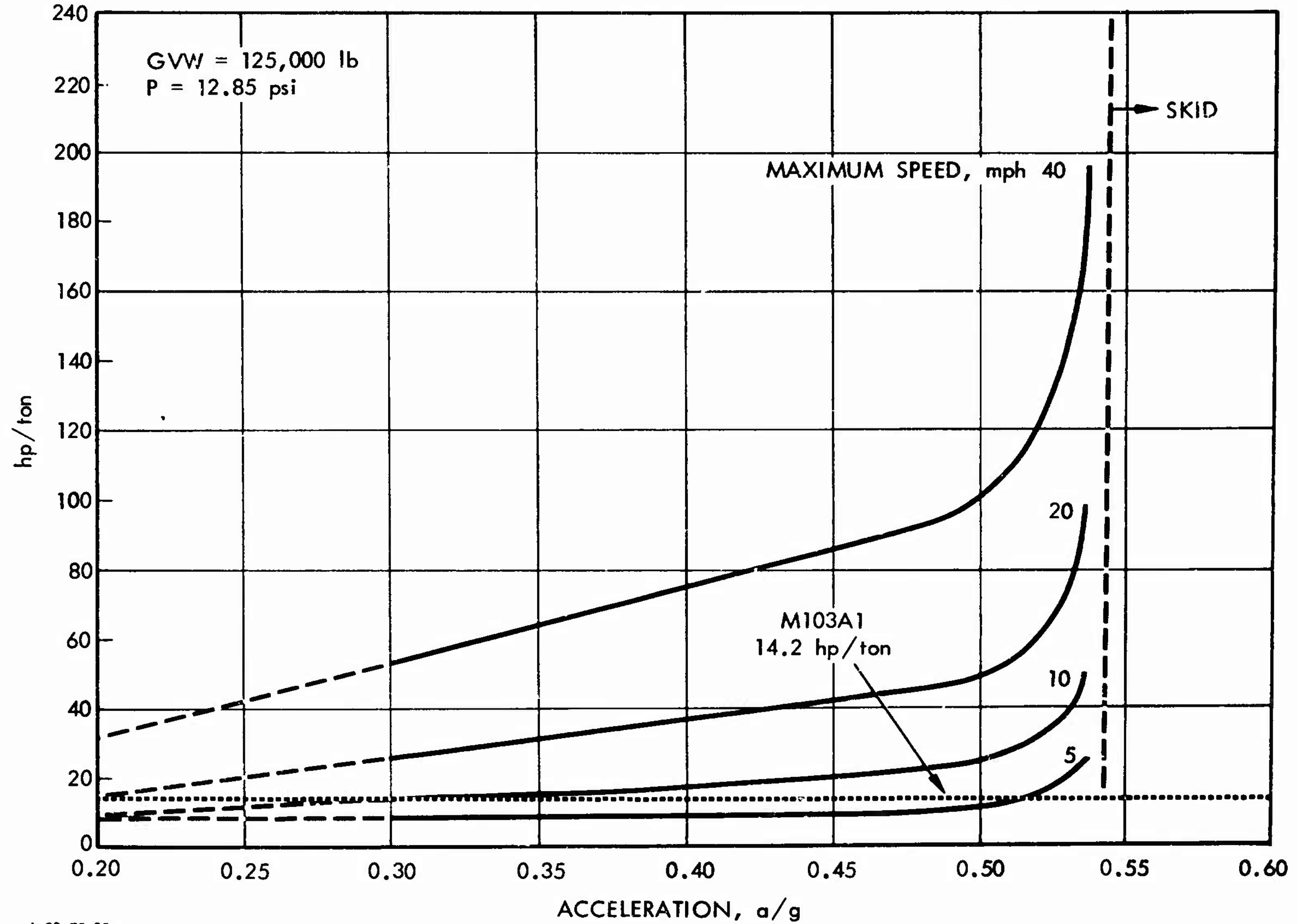

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FIGURE E-12. Power Requirements of M103A1 for Target Speeds, 40, 20, 10, and 5 mph, at Various Accelerations that Could Be Developec in Dry, Level Sand. Power is Limited by Track Skid

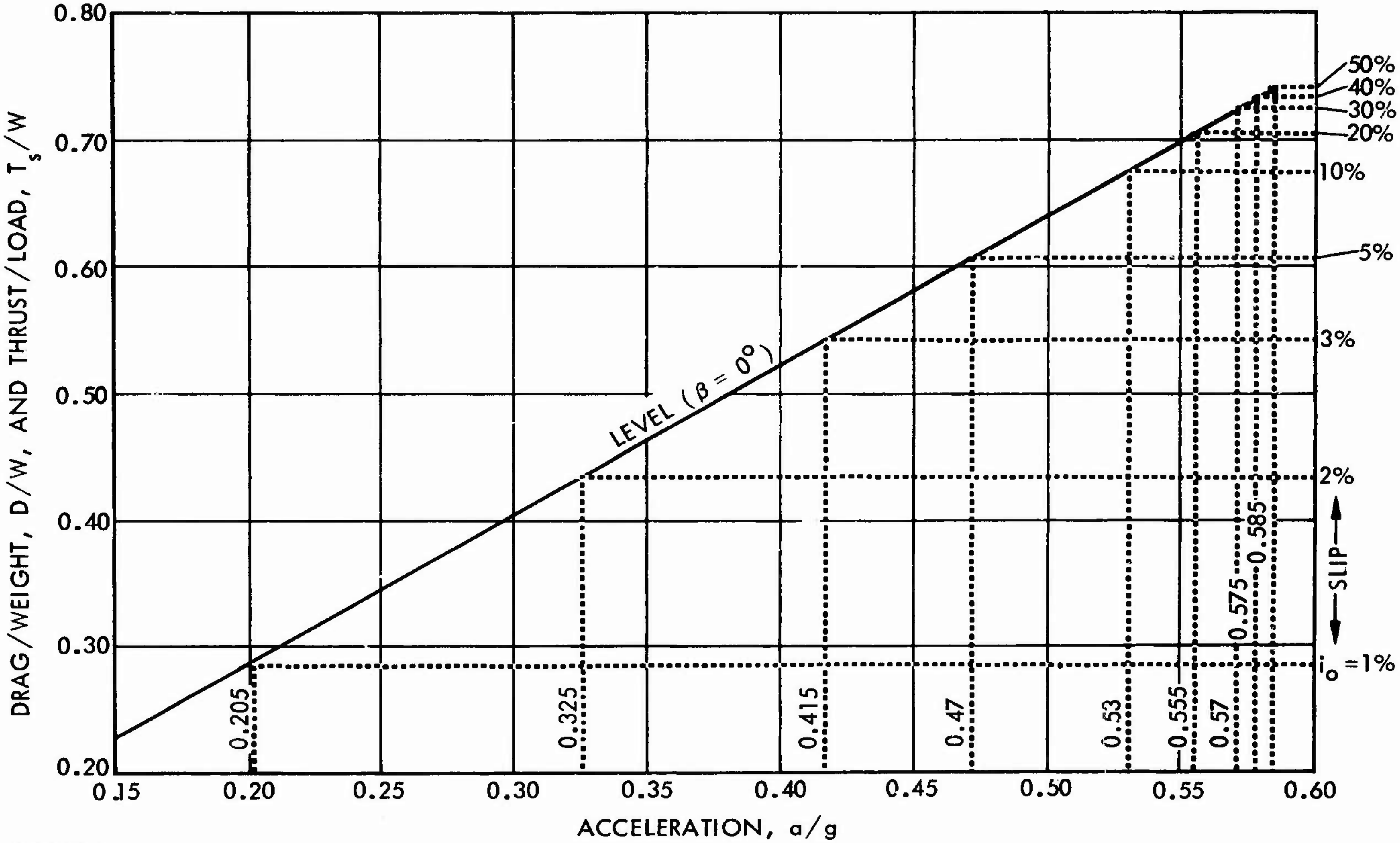

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FIGURE E-13. Performance of M113 in Dry Sand

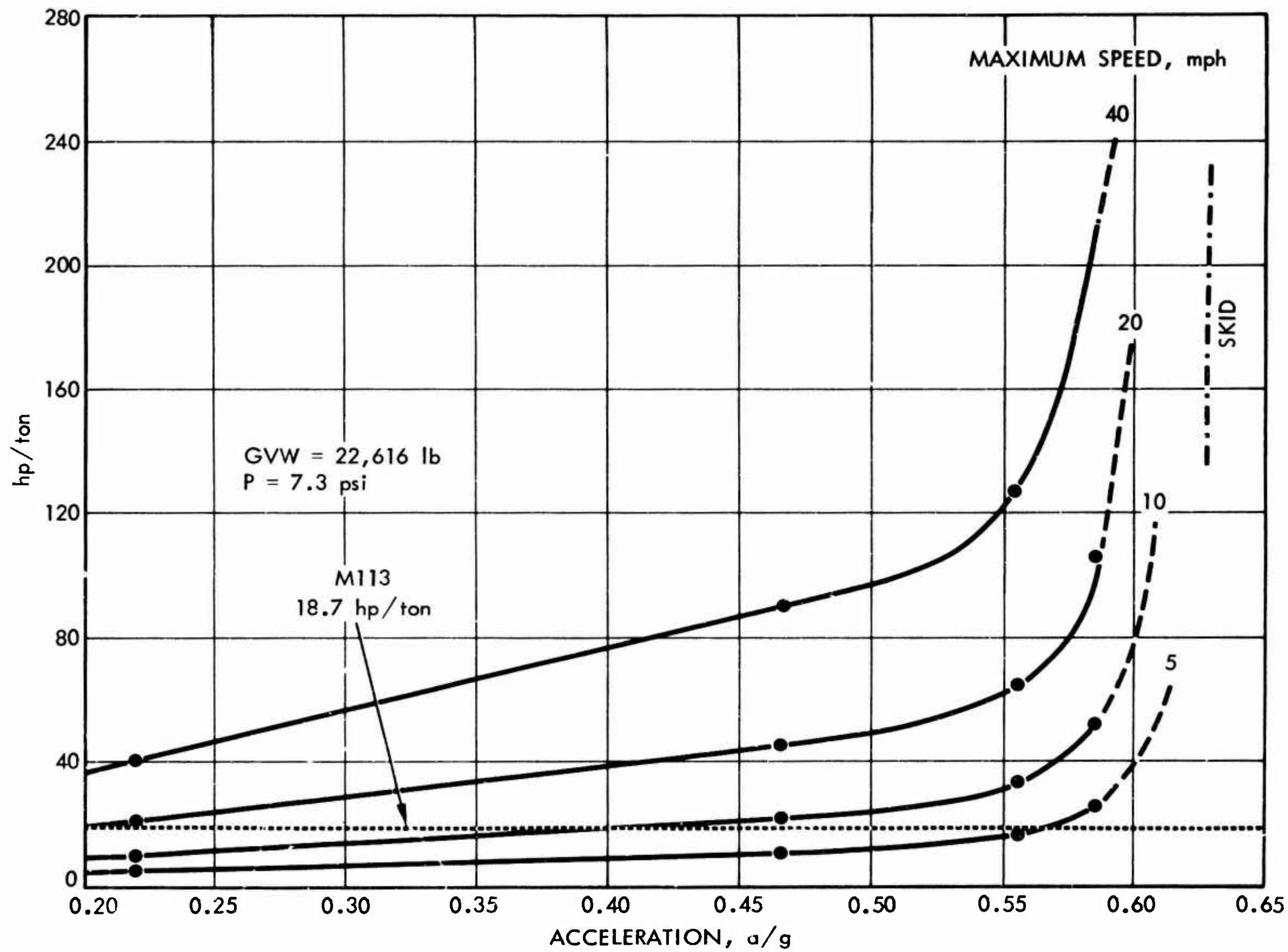

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FIGURE E-14. Power Requirement of M113 for Target Speeds of 40, 20, 10, and 5 mph at Various Accelerations that Could Be Developed in Dry, Level Sand. Power is Limited by Track Skid

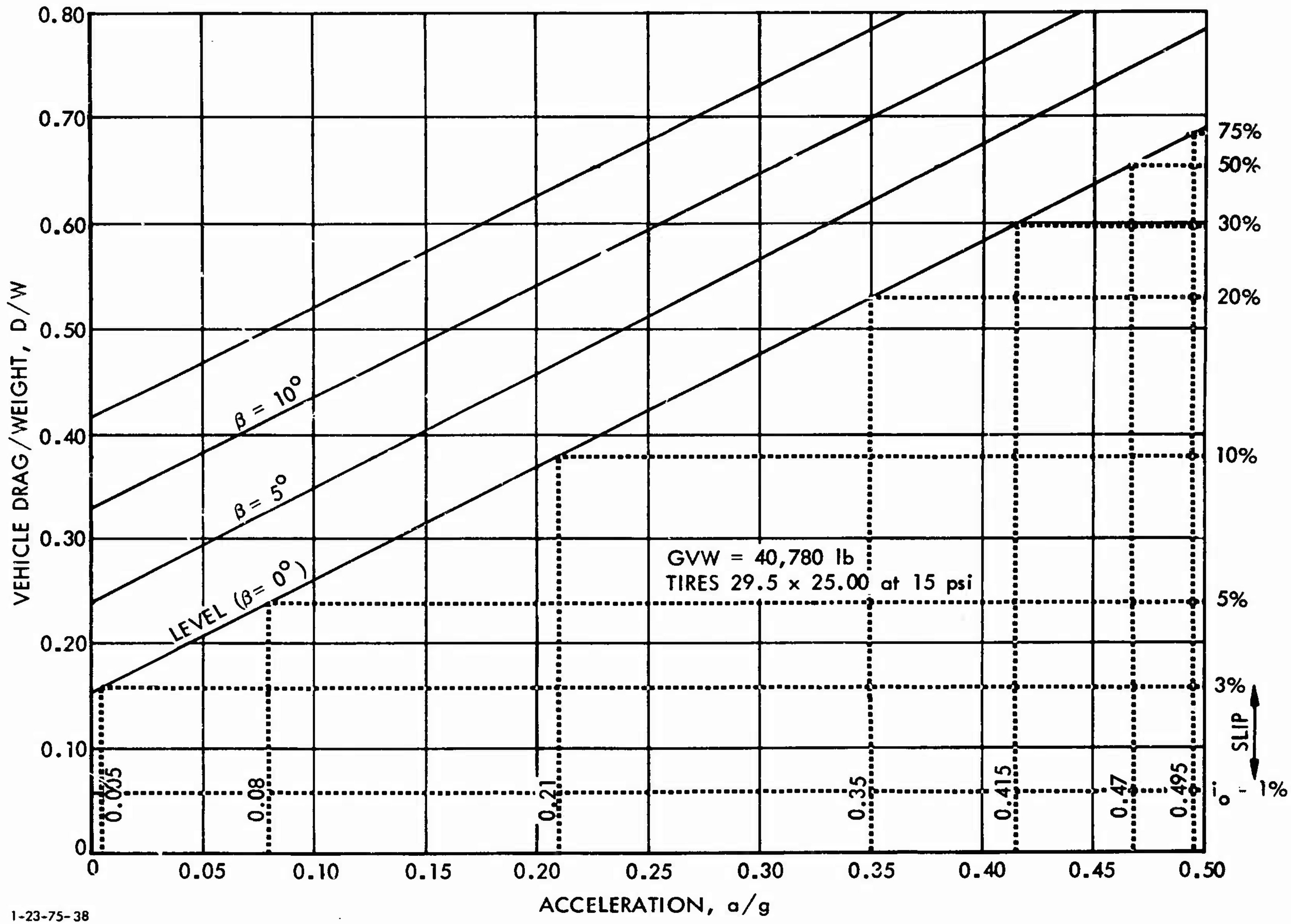

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FIGURE E-15. Performance of "Goer" 4 x 2 Vehicle in Dry Sand

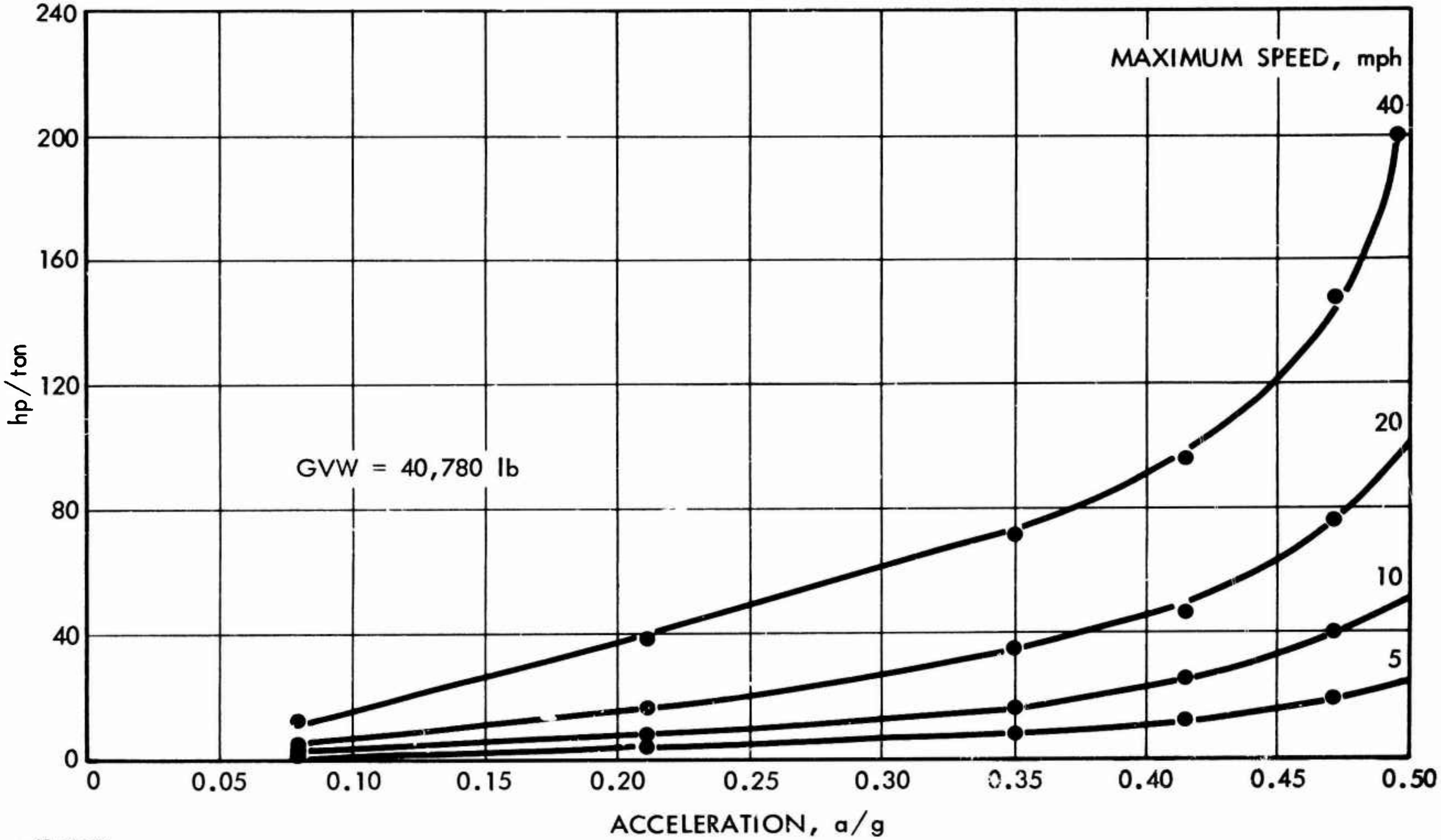

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FIGURE E-16. Power Requirement for "Goer" for Maximum Speeds of 40, 20, 10, and 5 mph at Various Accelerations that Could Be Developed in Dry, Level Sand. Power is Limited by Excessive Wheel Slip (Skid) by means of Eqs. (E.2), (E.3), and (E.4). As a comparison of the three vehicles under consideration, Fig. E.17 illustrates the difference between the TRACK and WHEEL. In order to emphasize the "highway characteristics" of the regular Goer with one-axle drive, the lower line was added. Finally, Fig. E.18 summarizes the computed results, in terms of hp/ton required to achieve the target speeds, with accelerations available in soil thrust at pertinent slips. Note that for "low mobility" requirements (up to 0.35 g acceleration) there is not much difference in power required. Beyond $a/g \cong 0.35$, the difference between the tracked vehicles remains insignificant, until high slip (skid) conditions are reached; then the vehicle with lower ground pressure (M113) is better (higher a/g) than that with higher ground pressure (M103A1). Track lengths are comparable (ℓ = 173 and 105 in.). However, wheeled vehicles cause performance to deteriorate (high slip) and requires more hp/ton very quickly after they reach critical a/g. In case of the Goer, the $(a/g)_{crit} \cong 0.3$. This unfavorable condition of wheel performance, even at a very low inflation pressure, is due to the shortness of the ground contact area, as explained in the next section on tractive effort.

E.5 TRACTIVE EFFORT

It is assumed that the tractive effort is defined by the horizontal component of force, which may be developed by the soil through its shearing strength. The total tractive effort, H, of a track or wheel will be

$$H = b\int_0^{\ell} \tau \, dx \ , \qquad \text{(E.7)}$$

where

τ = unit tractive effort

b = width of the load area

ℓ = length.

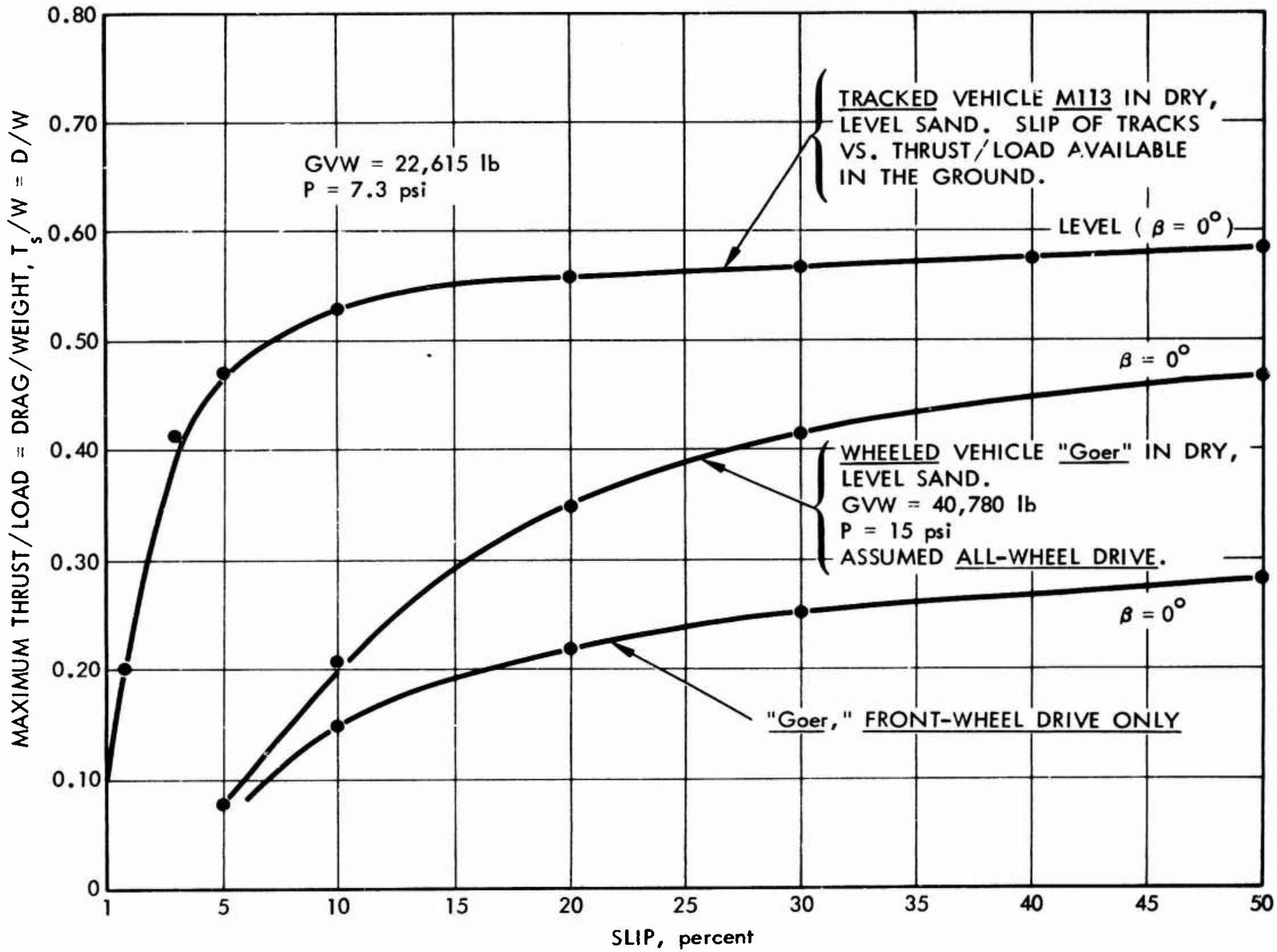

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FIGURE E-17. Comparison of Traction of a Wheeled and a Tracked Vehicle

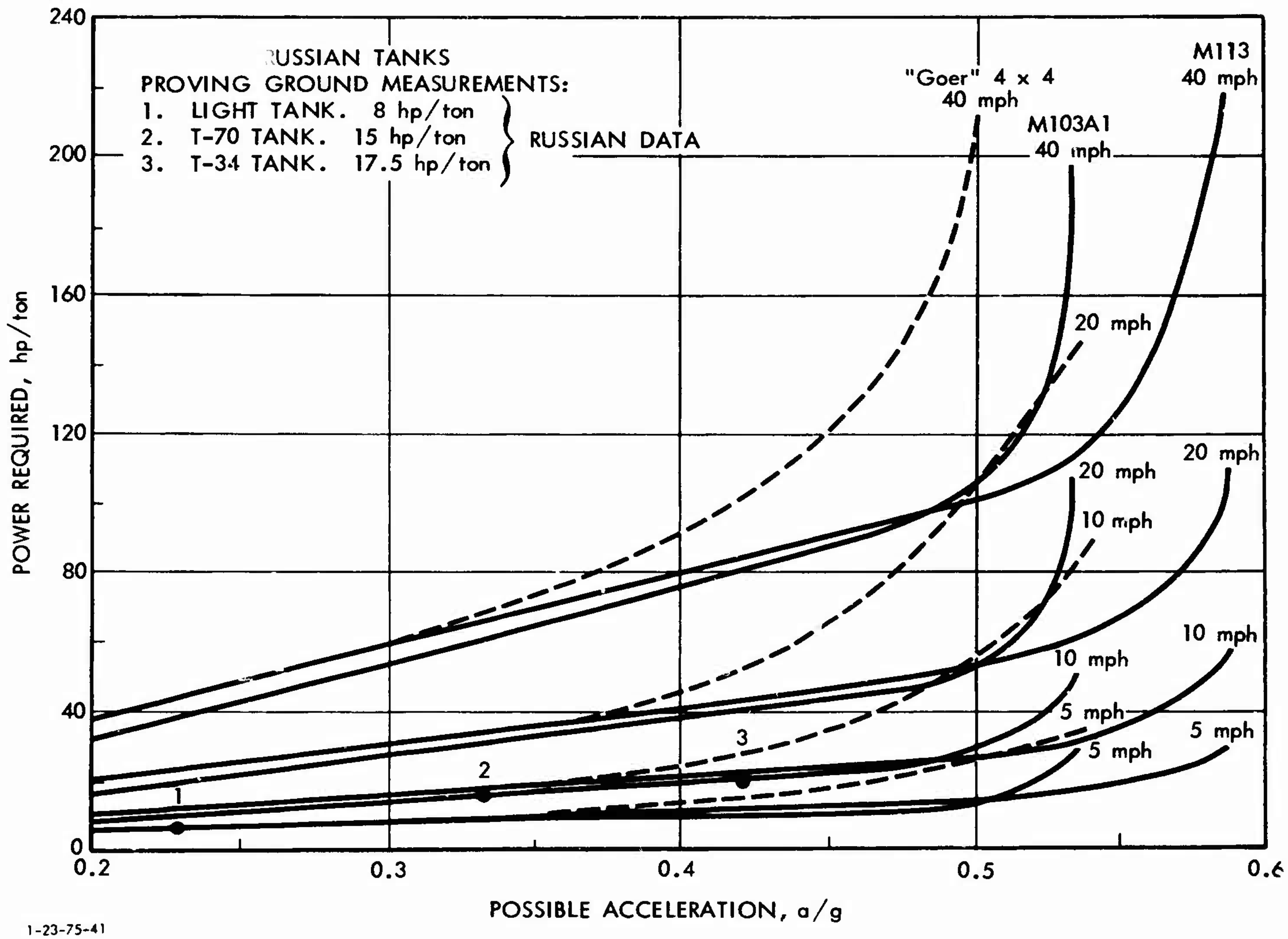

FIGURE E-18. Power Required to Attain Various Maximum Speeds with Various Accelerations on Level, Dry Sand

For a nonuniform distribution of load p, the integration of Eq. (E.7) becomes very cumbersome.

The amount of tractive effort available depends on soil distortion j (shearing strain). A study of the mechanics of vehicle slippage i_o has disclosed that the j value is not constant at particular points of the ground contact area, but increases linearly from zero to j_{max} along that area. Thus, soil distortion at any point located at distance x from the front of the ground contact area is

$$j = i_o x \quad . \tag{E.8}$$

The tractive effort, T_s, will be obtained in terms of $i_o \ell$, i.e., in terms of the product of vehicle slippage i_o times the length ℓ of the ground contact area. Figure E.19 shows the i_o values computed for tractive effort developed per unit of the contact area in a silt and sandy loam.

An important conclusion may be drawn on the basis of this example: if the track length is reduced and the width simultaneously increased so that the ground contact area remains constant, the maximum tractive effort available in the given soil can be developed, but only at the expense of increased slippage; i.e., speed of locomotion will be reduced. The following table gives typical numbers.

TABLE E-1. COMPARISON OF TRACTIVE EFFORT FOR WHEELS AND TRACKS

Track or Tire	Length of Ground Contact Area, in.	Slippage, Percent at Maximum Traction[a] Silt	Sandy Loam
Track	100	2.5	7.5
	50	5.0	15.0
	25	10.0	30.0
Low-Pressure Tire	10	25.0	75.0

[a]All figures approximate.

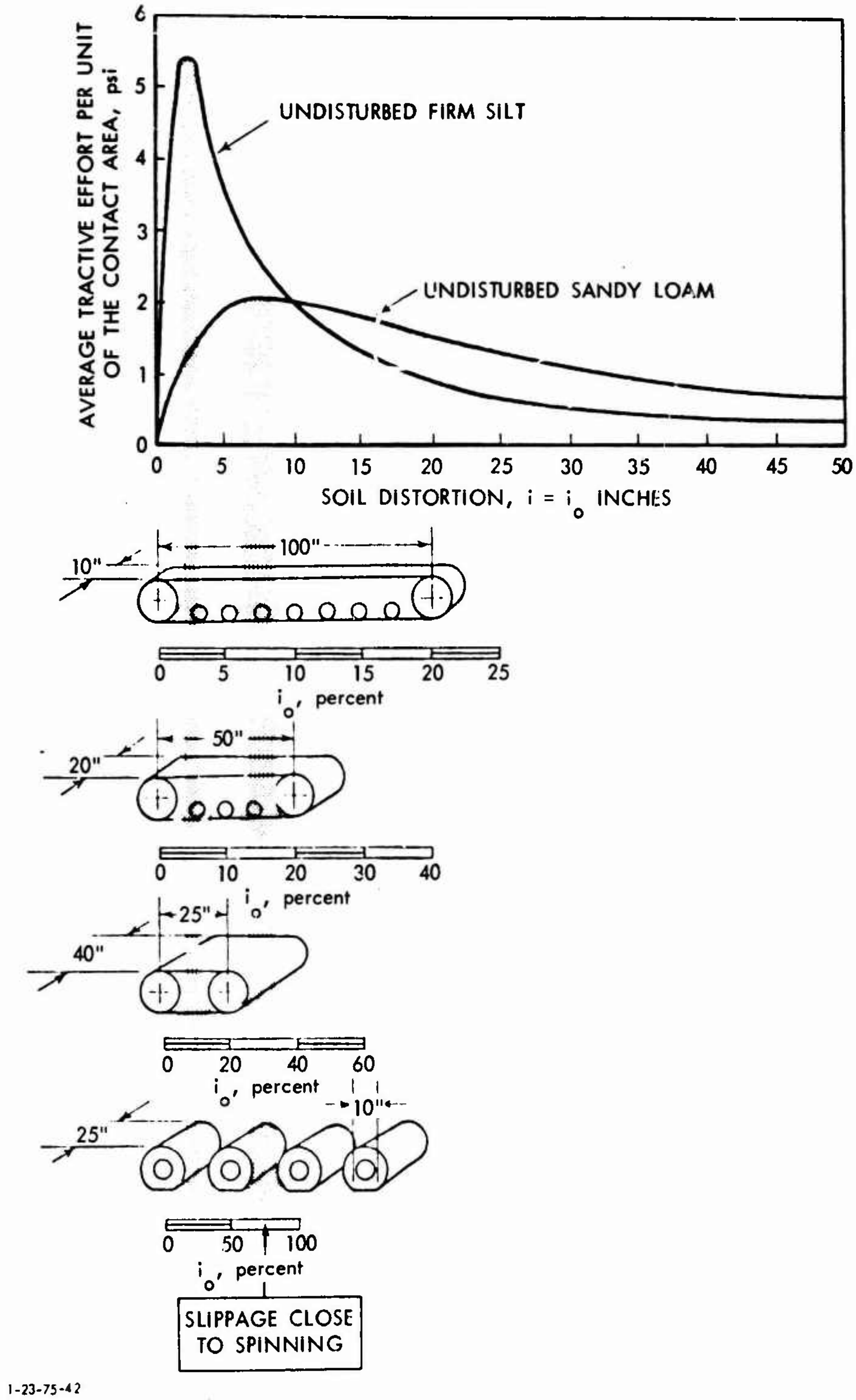

FIGURE E-19. Tracks Versus Wheels--Slippage. Relationship Between Slippage, i_o, and the Length of the Ground Contact Area for Undisturbed Sandy Loam

Thus, if the ground contact area of a track 100 in. long amounts to, say, 1,000 sq in., and is replaced by four low-pressure pneumatic tires which produce the same 1,000 sq in. of bearing area divided among four 10-in.-long areas, then the slippage of the wheeled vehicle at the peak of its traction must be ten times larger than that of the tracked vehicle. Seventy-five percent slippage indicates that the wheel is almost spinning, and such a vehicle may be easily stalled. Therefore, a wheel cannot replace a track unless it is of a sufficiently large diameter that the length of its ground contact area approaches the length of the corresponding track, and the slippage becomes tolerable.

It may be concluded that the magnitude of the unavoidable slippage of tracks and wheels associated with the development of tractive effort can be expressed in terms of the length of the ground contact area. In relation to a vehicle which develops maximum traction at i'_o slippage, having s' length of ground contact area, another vehicle having the same unit load but s'' length of contact area will develop slippage i''_o:

$$i''_o = i'_o \frac{s'}{s''} \quad . \tag{E.9}$$

Equation (E.9) shows the essential difference between the performance of tracked and wheeled vehicles, even when they have equal "flotation." Thus, where a track will move with ease, a wheel may spin.

E.6 CONCLUSION

The conclusion reached becomes more clear if Fig. E.18 is cross-plotted, as shown in Fig. E.20. Here, the desired levels of performance measured in terms of accelerations 0.3, 0.4, and 0.5 g are plotted in terms of "target" speeds vs. the required power in hp/ton. It is very difficult for a wheeled vehicle to match a tracked one if the accelerations required are high.

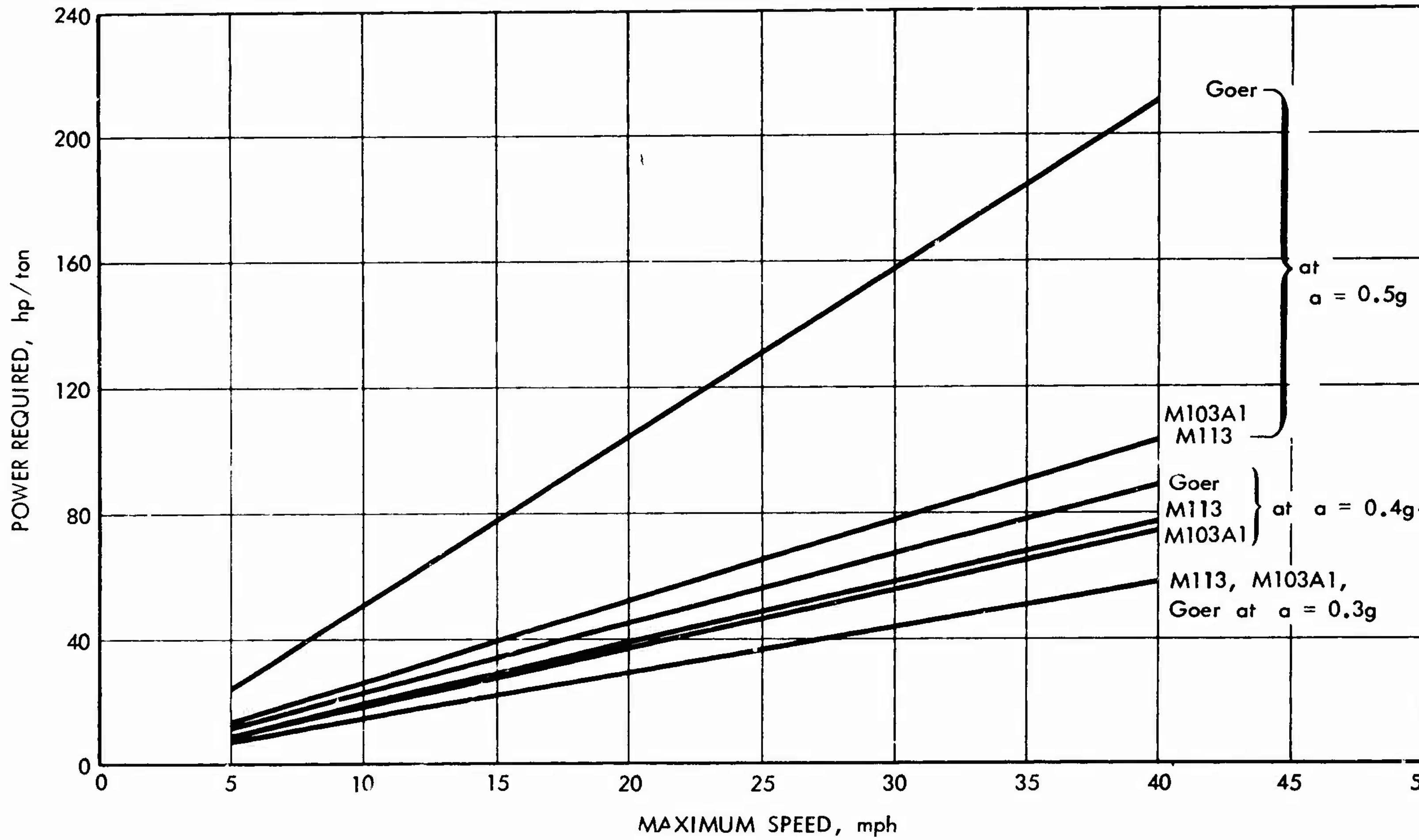

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FIGURE E-20. Power Versus Maxim m Sp d of M10A3 and M113 Tracked Vehicles and of the "Goer" (With 4-Wheel Drive) at . that Can Be Developed in Dry, Level Sand to Attain the Given Maximum Speea

At $a = 0.3$ g, there is practically no difference between the M113, the M103A1, and the Goer. Also, the tracked vehicles' power requirements remain invariant, even for accelerations of $a = 0.5$ g, notwithstanding the GVW (M113 ~10 ton, M103A1 ~56 ton). But the Goer departs rapidly from the tracked vehicles and quickly reaches a point of impracticality. Conclusions are:

1. Drag/weight ratios and power/weight ratios of tracked vehicles display great uniformity and similarity in frictional soils, independent of GVW.
2. Performance of these vehicles measured in terms of power and acceleration also is similar and uniform, notwithstanding the GVW.
3. Wheeled vehicles radically depart from the tracked vehicles, from the viewpoint of performance.
4. The power limit applicable to the given vehicle depends critically on the thrust-slip characteristics of the soil, and the type of the running gear.
5. All this sets the boundaries of optimum hp/ton, beyond which power cannot be usefully employed.
6. The need for a comprehensive study of such a problem is dramatized by the fact that further increase of power has entered a steep path of diminishing returns: the gain in acceleration, if justified by ground capability to absorb power, has become increasingly costly in terms of weight and fuel consumption.

E.7 DISCUSSION

Equation (E.6) defines the average power required for vehicle acceleration from zero speed to V_m at a constant acceleration a.

If it is expected, however, that the appropriate power reserve is available throughout the complete cycle of acceleration, the P/W value of Eq. (E.6) should be doubled. Thus, the ordinate scales of

Figs. E.12, E.14, E.16, E.18, and E.20 would express twice as much power as shown.

In such a case, the growth of required hp/ton with increasing acceleration quickly becomes prohibitive. This illustrates further the need for computations of power reserve in a more specific manner than assuming that the speed V_m will be reached in time t, if the engine develops N hp.* The nature of the problem is depicted in Fig. E.21 which is, in essence, the reproduction of Fig. E.18, with the left-hand corner of the graph extended to zero acceleration. Figure E.21 shows that we are now approaching the steep portion of the hp/ton curve, and any increase of power becomes more costly. The accelerations of M60A1 and XM1 quoted by Gen. Baer in conjunction with estimated performance of tanks in the 1980s were plotted in Fig. E.21 as reference points.

It should be noted that the soil considered here (i.e., sand) is not a critical soil. As a matter of fact, it is a very strong soil which can absorb much power. This is why the hp/ton figures can run high. But deserts and sandy soils are only a part of terrain structure. Many clayey soils and loams that extend over large surfaces of the globe, together with organic cover, may be very slippery when wet. They cannot absorb the power, as shown in Fig. E.21, and the vehicle with too many hp/ton will only spin the treads, thus raising a very serious question of "how much is enough." Similar questions cannot be avoided when considering snow or icy, frozen ground.

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*Compare the article by Gen. R.J. Baer in No. 3 Armor issue, Vol. LXXXIII, May-June 1974.

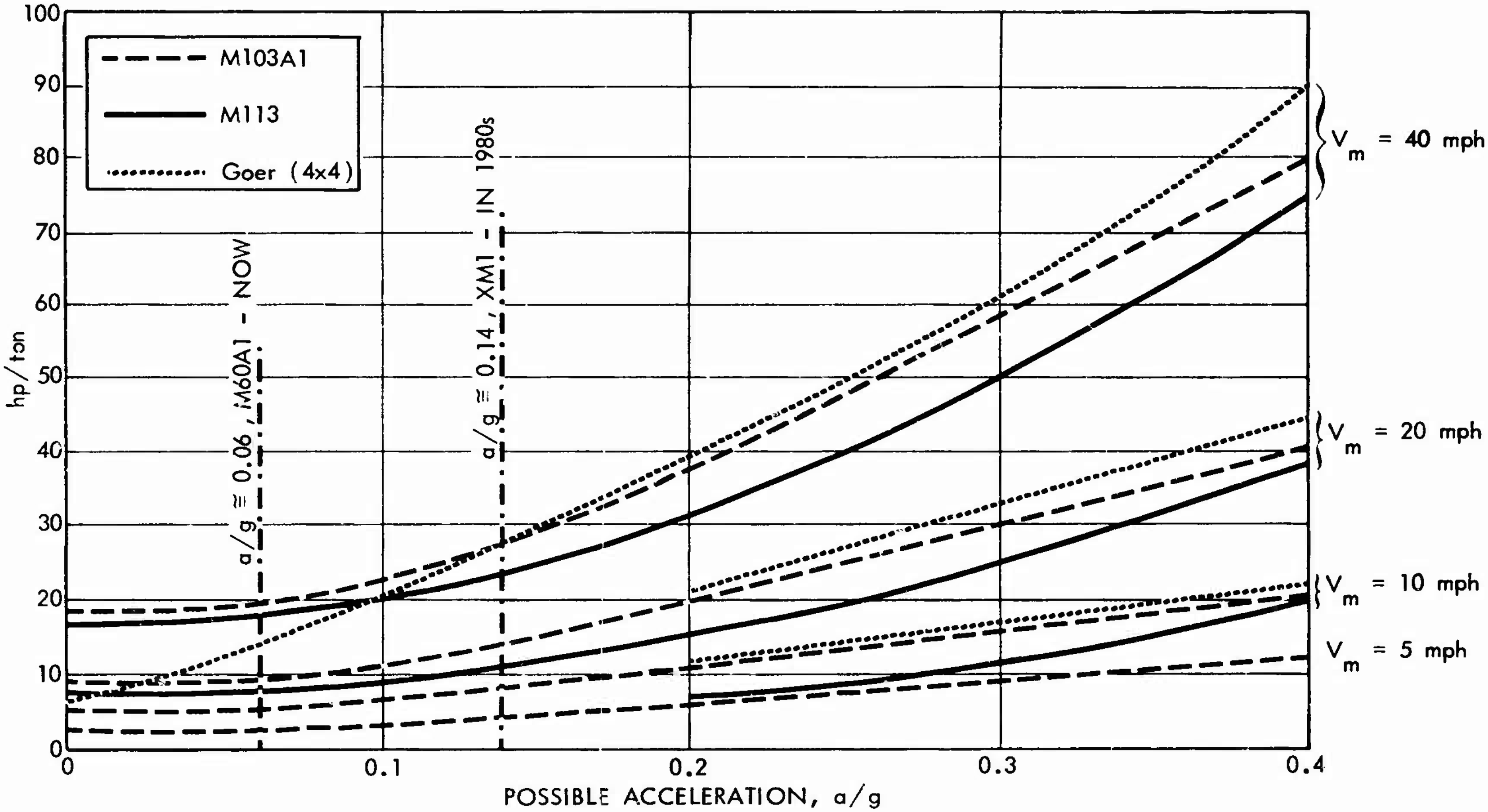

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FIGURE E-21. Average Power Required to Attain Speeds, V_m, with Various Accelerations, on Dry, Level Sand

APPENDIX F

SPECIFIC POWER OF INTERNAL COMBUSTION ENGINES

P.C.T. de Boer

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APPENDIX F

SPECIFIC POWER OF INTERNAL COMBUSTION ENGINES

An important parameter in choosing a power plant for vehicular use is its specific power with respect to weight (power-to-weight ratio). Other ways of expressing specific power are with respect to volume (power-to-volume ratio), or with respect to cost (power-to-cost ratio). In most cases, the specific powers so defined bear a direct correlation to each other. The purpose of this appendix is to discuss some of the important trends in the dependence of specific power (or its inverse, specific weight) on various engine parameters.

First, we consider normally aspirated diesel engines. Figure F.1 shows specific weight (weight-to-power ratio) for a number of such engines, as a function of output per cylinder. The data shown correspond to maximum power output as listed on manufacturers' specifications (Ref. F.1 and Table B.7, Appendix B). In some cases, they probably represent an optimistic point of view. Nevertheless, it is believed that the data correctly represent the various trends of present interest. The first of these trends is the increase of specific weight with power output at large power outputs. Basically, this trend derives from the fact that mean effective pressure (mep) and piston speed are subject to limitations independent of cylinder size. Under conditions of maximum power output, the mep of normally aspirated engines is determined mostly by the compression ratio, which is limited by practical considerations. As a result, the mep in normally aspirated engines is no larger than about 100 psi (see Ref. F.2, Fig. 17-4 and Ref. F.3, Figs. 1-3). Similarly, the maximum piston speed is limited because the speed of sound of air entering the cylinder, as well

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as the rate of combustion, are prescribed quantities. For conventional designs, the maximum value is on the order of 1,000 ft/sec (see Ref. F.2, Fig. 17-5 and Ref. F.3, Fig. 1). By definition, the power output per cylinder is the product of mep, piston speed, and piston area for two-stroke engines, and one half that product for four-stroke engines. As a consequence, maximum power output per cylinder increases roughly proportional to piston area, or to b^2, where b denotes the cylinder bore. On the other hand, weight of the engine is roughly proportional to cylinder volume, i.e., to b^3. It follows that the ratio of weight-to-power output is roughly proportional to b, i.e., to the square root of the power output. The dashed line in Fig. F.1 shows the slope of such a line. It indicates the trend at power outputs larger than 30 hp per cylinder quite well, supporting the rationale just given.

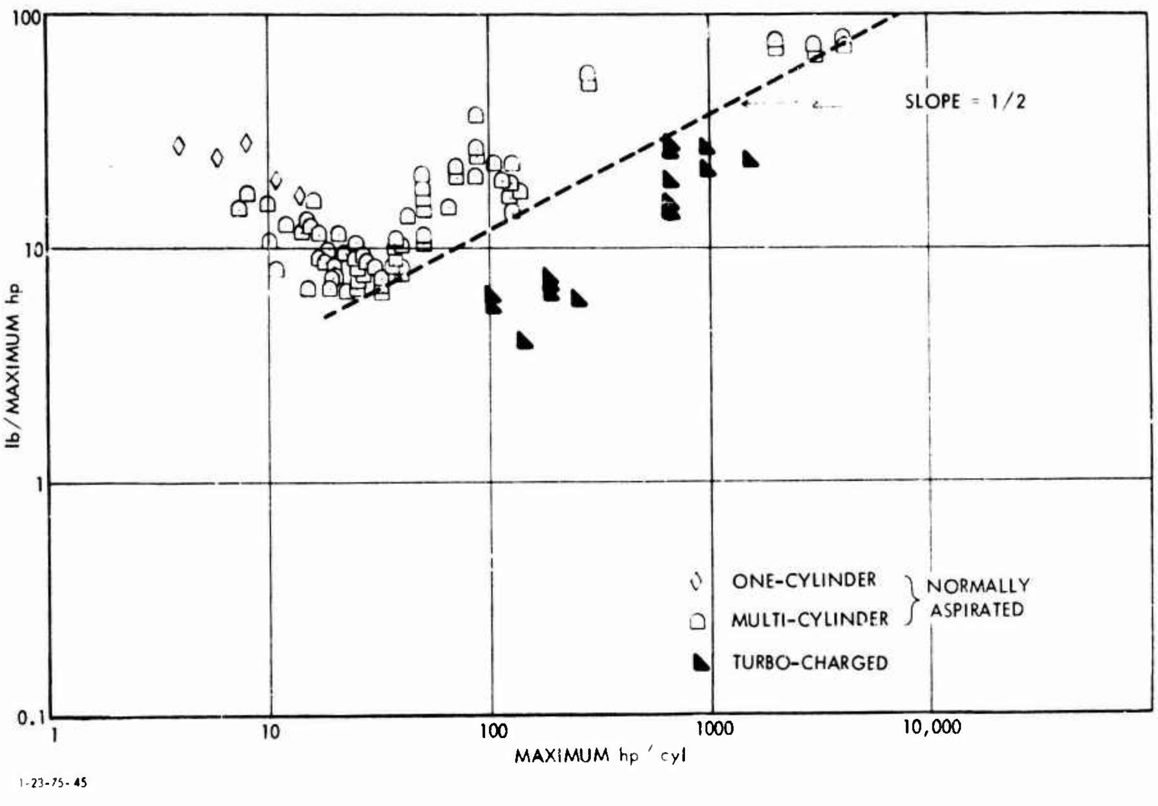

FIGURE F-1. Specific Weight of Diesel Engines as a Function of Maximum Power Output per Cylinder

Below 20 hp per cylinder, the data of Fig. F.1 do not follow the similarity rule discussed, rather, they show an increase of weight-to-power output as output decreases. This results from increased heat losses to the cylinder walls when the cylinder bore is small. At large bores, heat losses to the cylinder walls represent only a small fraction of the total heat content of the combustion gases, while at small bores the fraction becomes large enough to appreciably reduce power output. The order of magnitude of the bore for which heat losses become appreciable can be estimated analytically; it comes out to about 8 inches. It is difficult to make a reliable calculation of the power output of small engines, taking account of the heat losses. As a result, no simple similarity rule is available for the behavior of the data of Fig. F.1 below 20 hp per cylinder.

It follows from Fig. F.1 that, for a given power output, the specific weight of large engines can be decreased by decreasing bore size while increasing the number of cylinders to maintain the same piston area. Obviously, the extent to which this can actually be done is limited, because in engines with a large number of cylinders serious design problems would result and maintenance costs would be higher. From the point of view of specific weight alone, it would appear that the optimum cylinder power is 30 hp. It is interesting to note that vehicular engines tend to follow this pattern, i.e., 90-100 hp, three-cylinder; 180-200 hp, six-cylinder; and 240-280 hp, eight-cylinder.

At still higher power levels, the number of cylinders becomes excessive and other techniques are used to keep specific weight within bounds. These other techniques involve increasing mep or piston speed, or both. There are some limits to what can be done in these areas, however. As mentioned above, maximum piston speed is limited because the speed of sound of air entering the cylinder has a fixed value. Large pressure drops occur when the air velocity approaches the speed of sound. Additional disadvantages of high piston speeds are increased engine friction, increased inertial stresses and vibration levels, more difficult control of fuel injection, increased noise level, and more stringent requirements on the fuel which can be burned. Furthermore, low piston speed and mean effective pressure tend to be associated .ith low maintenance, high reliability, and long life--advantages which are compromised by raising piston speed and mep. Nevertheless, to meet the demand for lower weight at higher power levels, diesel manufacturers started around 1960 to use both higher meps and higher piston speeds. This has led to great improvements in the specific power outputs of diesel engines. Most of these improvements have resulted from increased mep attained by supercharging the engine. Simple single-stage supercharging will increase mep by 40 percent to 60 percent, giving rise to corresponding increases in specific power as the data on turbocharged engines in Fig. F.1 indicate. The best results have been obtained with two-stage turbocharging with inter-cooling and aftercooling. Mep values of the order of 250 psi have been reached. Improvements have also been made in piston speed, which in some cases has been successfully increased to about 2,000 ft/sec. Because limitations independent of cylinder size still apply to both mep and piston speed, the same similarity rule may be expected to hold for weight-to-power ratio as a function of power output per cylinder, as holds for the normally aspirated engines. However, because developments in this direction have been relatively recent and relatively few, the data available are insufficient to provide a definitive test of the rule.

The data of Fig. F.1 have been replotted in Fig. F.2 with total power output instead of power output per cylinder as the horizontal coordinate. Although such a plot does not do justice to the fundamental importance of the output per cylinder, it provides a meaningful comparison of different engine types. Corresponding to the single dashed line of Fig. F.1, there is a one-parameter family of dashed lines in Fig. F.2, the parameter being the number of cylinders per engine. The lines shown are for four-, eight-, and twelve-cylinder diesel engines. It follows that all four-cylinder engines fall to the left of the four-cylinder dashed line in Fig. F.2, all eight-cylinder engines to the left of the eight-cylinder line, etc.

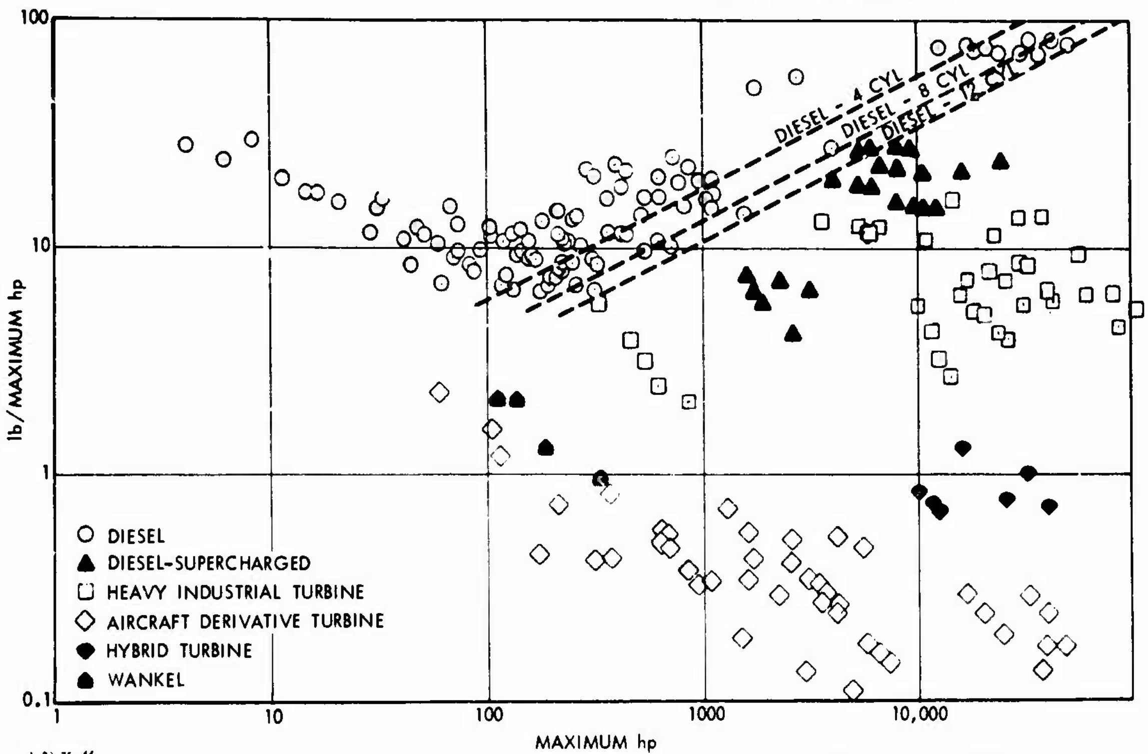

FIGURE F-2. Specific Weight of Various Engine Types as a Function of Maximum Power Output

Also shown in Fig. F.2 are data for gas turbines based on the manufacturers' specifications of Ref. F.4. Two quite different classes of gas turbines are represented: the so-called "heavy-industrial" type and the "aircraft-derivative" type. The former have long been available, and are large, conservatively designed engines with high power outputs and low specific power Their TBO (Time Between Overhauls) tends to be very long (up to 100,000 hours). As the name implies, the aircraft-derivatives find their origin in developments in the aircraft turbine industry. These developments are relatively recent, and have led to specific powers that are much better than those of the heavy-industrials. The difference can be as large as a factor of 100, as can be seen from Fig. F.2. While initial cost of the two types is comparable, the TBO of the aircraft derivatives tends to be less favorable. The high power output is obtained by using sophisticated designs, including materials of low specific weight, and high gas temperatures. Gas temperatures are limited by the properties of the turbine blades, in which important improvements have been made during the last 15 years. As a consequence, the trends shown by the gas turbine data of Fig. F.2 represent, to a large extent, a situation that has not yet stabilized. Aircraft-derivative turbines have been designed to compete with the heavy-industrials, in heavy-industry applications. Also, there is a family of hybrids, using an aircraft-derivative gas generator in combination with a heavy-industrial-type turbine.

As pointed out by Taylor and Taylor (Ref. F.2), the similarity rules for turbines fundamentally are the same as for diesel engines. The basic consideration is the stress in the turbine blades as determined by tip speed. For given tip speed and otherwise similar engines, the power output will be proportional to the square of the linear dimension, while the weight is proportional to the third power of the linear dimension. This leads to the same similarity rule at high power outputs as for diesels, i.e., specific weight increases directly as the linear dimension. For small power outputs, the increase of weight-to-power ratio arising from heat losses is a trend that also is followed by gas turbines. The low power trend is seen in the data on Fig. F.2, but the high power trend is masked by other factors, notably the trend to increased gas temperatures which significantly reduces weight requirements. This is illustrated by Fig. 3-11 of Ref. F.5, which shows that, for any given maximum temperature during the cycle, there is a pressure ratio at which power output is maximum. Increasing the allowed maximum temperature significantly influences maximum power output. It also allows the use of a greater pressure ratio at maximum power output, thus improving efficiency. It appears that gas turbines have minimum specific weight at outputs in the range of a few thousand horsepower. This conclusion is partly based on the extensive data for aircraft gas turbines of Ref. F.6. Figure 5 of Ref. F.6 shows that the gas generator minimum weight-to-airflow ratio is achieved at about 100 lb_m/sec. Multiplying this mass flow (m) with $\frac{1}{2} V^2 \eta_t$, where V is the exit velocity and η_t the turbine efficiency, inserting reasonable values for V and η_t, and assuming that the turbine scales the same way as the gas generator, leads to a power output of a few thousand horsepower. Alternatively, the power output at minimum specific weight can be estimated by taking the ratio of the mass flow to the specific air mass flow. A reasonable value for the latter quantity is about 0.020 lb/hp sec (see Ref. F.7, p. 68), yielding a power output at minimum specific weight of 5,000 hp.

For completeness, both the reciprocating and the rotating spark ignition engine should also be mentioned. Cylinder size of the reciprocating spark ignition engine is limited by combustion knock (auto-ignition of the end mixture). As a consequence, engines of this type are not practical at high power outputs. At low power outputs, the specific weight is quite favorable, and shows the same trends as diesel engines. This is illustrated in Fig. F.3, which is based on the aircraft engine performance documented in Refs. F.8 and F.9. Although the specially developed aircraft diesels described in Ref. F.9 have much lower specific weights than the diesels listed in Ref. F.1, they still are inferior in this respect to the reciprocating spark ignition engines. The latter generally are easier to start and control, but have higher fuel consumption and maintenance expenses. They have not found general use at power levels above a few hundred horsepower, although some of the engines represented in Fig. F.3 had outputs of a few thousand horsepower (see Fig. F.4).

The rotary spark ignition has become practical only recently. Its main promise is in its relatively low specific weight as shown by the Wankel engine points plotted on Fig. F.2 (Ref. F.10). However, the rotary spark ignition engine suffers from high specific fuel consumption and high maintenance costs. Both are related to the difficulty of achieving satisfactory seals for the combustion chambers. Apparently, current Wankel engines use rich fuel mixtures to aid in providing lubricants for the seals, and to aid combustion. As with the reciprocating spark ignition engine, combustion chamber size is limited, and large power outputs must be achieved by using many rotors. At

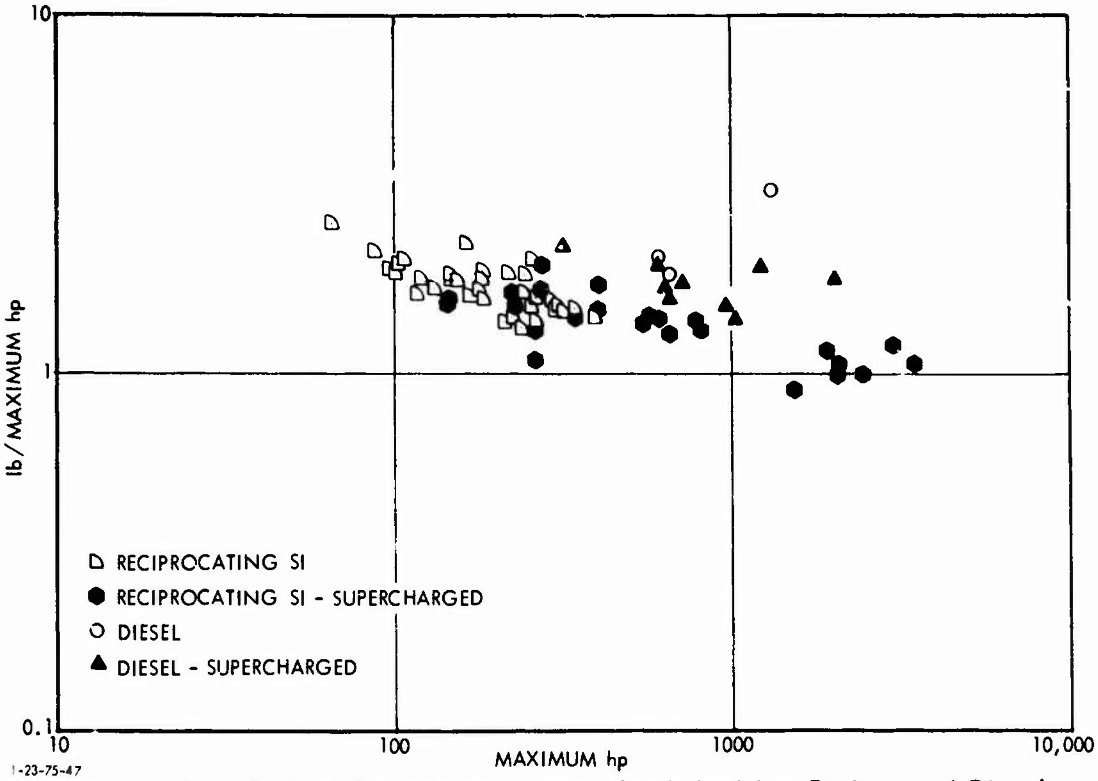

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FIGURE F-3. Specific Weight of Reciprocating Spark Ignition Engines and Diesel Engines as a Function of Maximum Power Output per Cylinder (Data points are based on Refs. F.8 and F.9, and apply to aircraft engines only)

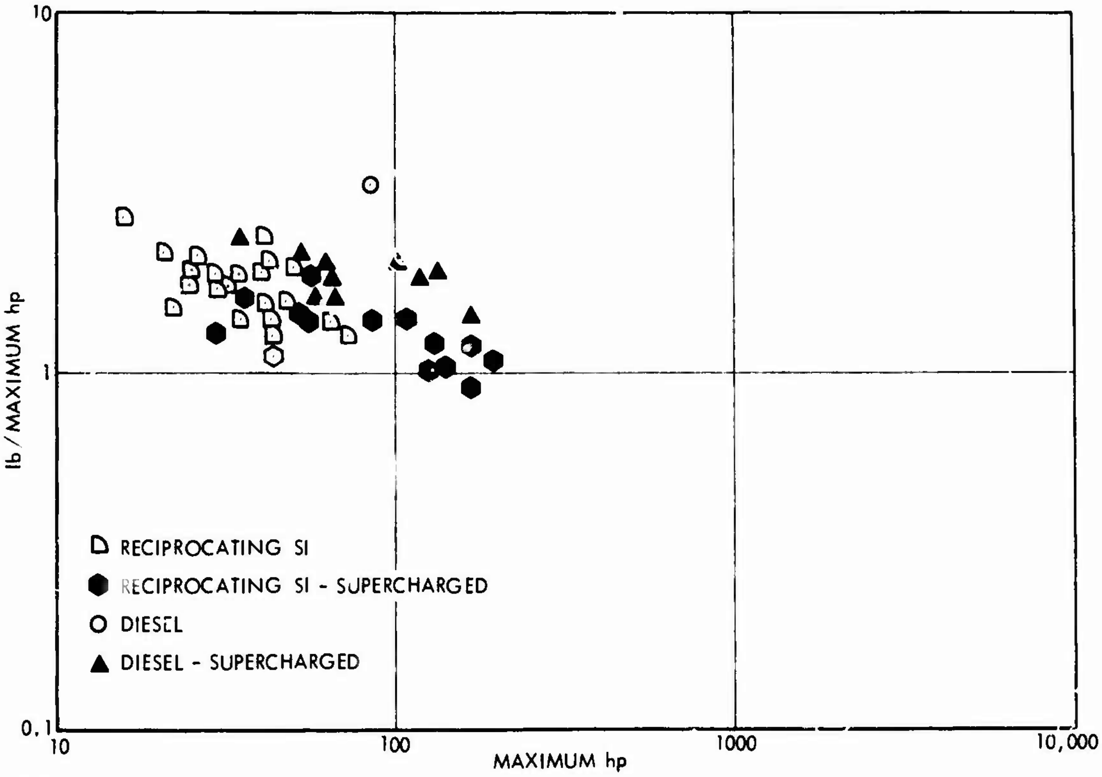

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FIGURE F-4. Specific Weight of Reciprocating Spark Ignition Engines and Diesel Engines as a Function of Maximum Power Output (Data shown correspond to Fig. F-3) present, sizes are up to a few hundred horsepower, and it seems unlikely that specific weight can be much improved over the data points shown in Fig. F.2.

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APPENDIX G

NUCLEAR PROPULSION TECHNOLOGY

P.C. Bertelson

CONTENTS

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APPENDIX G

NUCLEAR PROPULSION TECHNOLOGY

G.1 INTRODUCTION

Roughly 20 years ago, the Nautilus demonstrated the feasibility of nuclear power for ships. Since then, more than 200 other vessels have been built with reactors to replace the boiler/fuel-tank portions of the usual marine steam-turbine plant.

In this period, nuclear reactors have also been extensively used for large electrical generating plants. They have not been used for autos, tanks, or locomotives. In the case of aircraft, extensive, though unsuccessful, R&D work has been done in an effort to develop a suitable nuclear-propelled vehicle. This suggests the limitations, where propulsion is concerned, of properly shielded reactor power plants.

Whether, in the future, nuclear plants become more useful for propulsion naturally depends on how these plants evolve in comparison with alternative power plants. Such a comparison largely depends upon two rather conventional indices of performance:

- Specific weight, lb/hp, and
- Specific price, $/hp.

One might have added specific volume to those. Plant volume is important for some vehicles, submarines for example, although for most other vehicles weight is of primary importance. Also, the volume of a nuclear plant is automatically rather well controlled in a vehicle application through the effort to limit plant weight and price, as will become apparent. Hence, power plant volume will not be considered.

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Organizationally, this paper will first tabulate the performance of existing nuclear plants in order to indicate present accomplishment. From this, there are a number of attractive designs that have developed and these lead in turn to a few reasoned projections of future performance. The purpose is to determine what level of improved performance may be expected in the future, and where research may be needed to achieve these improvements.

G.2 CURRENT ATTAINMENT

The vehicles using nuclear power are, naturally, ships because these are the only vehicles able to use large, heavy power plants. Outside of warships, four merchant-type nuclear vessels have been constructed and are clearly described by the four nations which built them. All are based upon pressurized-water reactors and their general specifications are given in Table G-1.

TABLE G-1. GENERAL SPECIFICATIONS OF VESSELS POWERED BY NUCLEAR REACTORS

Vessel	Displacement (Tons)	Speed (knots)	Horse-power	Shielding (Tons)	Weight Reactor Plant (Tons)	Weight Machinery (Tons)	Specific Weight Power Plant (lb/hp)
SAVANNAH	21,850	20.25	22,000	2400	2760	1130	389
OTTO HAHN	25,812	15.75	10,000	1100+	2050	1000	610
LENIN	16,000	18.0	44,000	1963	3017	2750	262
MUTSU	10,400	16.5	10,000	2260	--	--	--

Some observations from the table are important. None of these reactor power plants is lighter than 2,000 tons. The Russian icebreaker Lenin happens to have three reactors, but it still has the smallest specific power plant weight. This is true even though the turbine-electric drives used are quite heavy compared to the steam turbines used by the other vessels. The dominant reason for the difference in specific weight is the shield weight required, which, the data suggest, is relatively independent of power level. Presumably, the specific weight might be even lower for plants with much larger power, as implied in Fig. G.1.

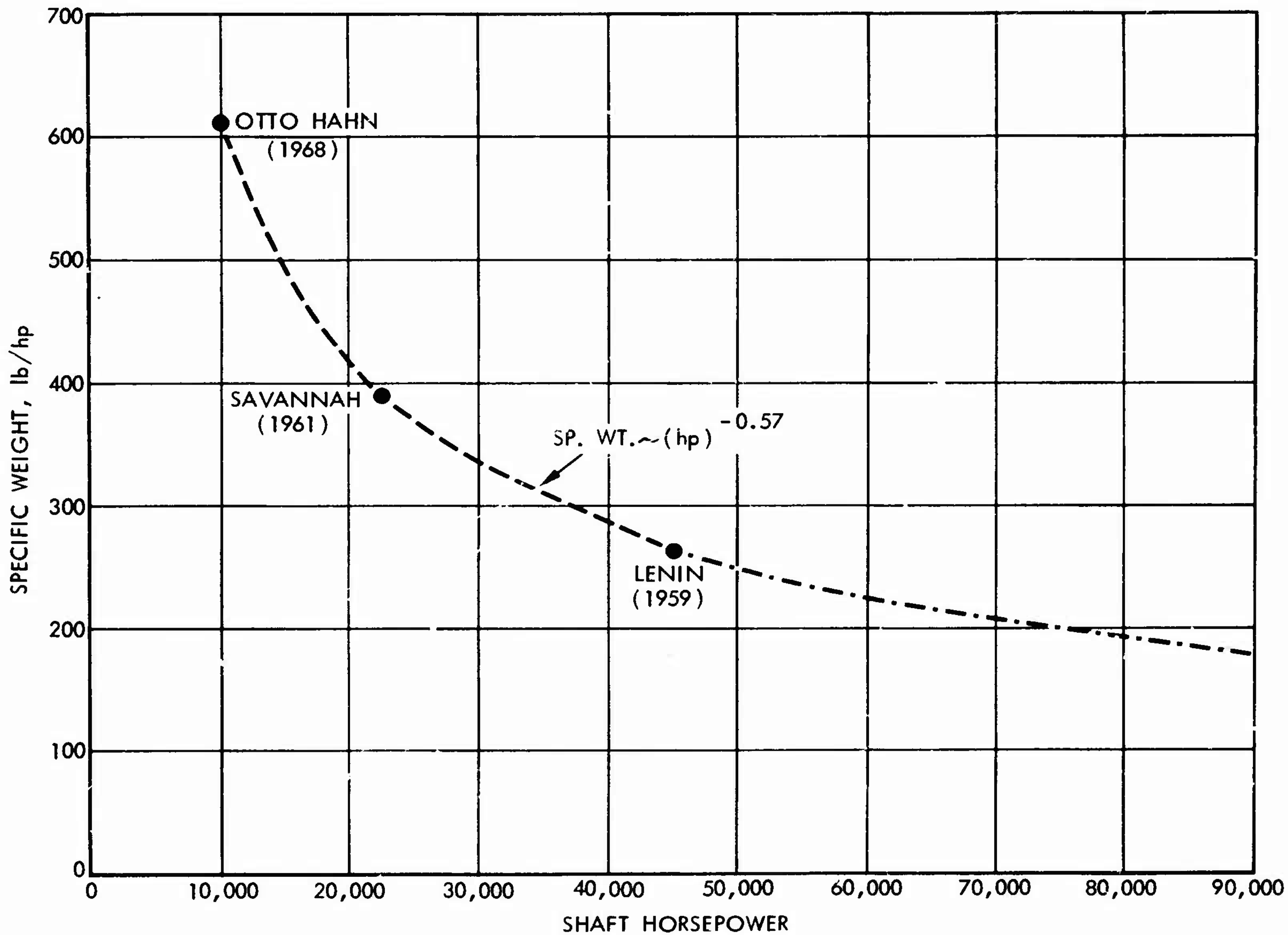

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FIGURE G-1. Specific Weight Versus Horsepower, Merchant-Type Marine Nuclear Power Plants

One would like to compare these civilian power plant specific weights with those for naval plants. Since the latter are not published, a possible range of specific plant weights will have to be inferred. A quotation from Marks' Handbook (4th Ed., 1941, p. 1527) is helpful:

> According to Admiral Bowen, machinery weights of high-powered naval vessels, fitted with geared turbines (based on full-power conditions) are about 27 and 40 lb/shp for destroyers and cruisers, respectively. This relatively low weight is due to the high revolutions employed with such machinery, the great power developed, and the care in design.

A nuclear plant carries its own fuel. For comparison purposes, therefore, we must add to these machinery weights for naval vessels the plausible weights of fuel consumed. This is done in the following simple tabulation:

Parameter	Vessel Type: Destroyer	Vessel Type: Cruiser
Top speed, assumed	33 knots	33 knots
Endurance at top speed, assumed	25 hours	100 hours
Weight fuel consumed (for sfc of 0.6 lb/hp-hr)	15 lb/hp	60 lb/hp
Weight of power plant, assumed	27 lb/hp	40 lb/hp
Apparent total weight, conventional power plant plus fuel	42 lb/hp	100 lb/hp

Now let us see whether there are material differences between the weights of U.S. warships that are oil-fired and those that have nuclear plants. The best comparisons are probably between the following pairs of similar vessels. None of these vessels is as light as a destroyer. Accordingly, it was assumed that the oil-fired power plants, with their fuel supplies, weighed 100 lb/hp. Attributing the entire weight differences to the respective nuclear power plants, it appears that the nuclear power plant of the LONG BEACH might have a specific weight of 150 lb/hp and the plant for the BAINBRIDGE could weigh 122 lb/hp.

Vessel	Horse-power	Full-Load Displacement (Tons)	Year of Commissioning	Waterline-Length (ft)
LONG BEACH, nuclear	80,000	17,350	1961	721
ALBANY, oil-fired	120,000	17,500	1946 & 1962	664
BAINBRIDGE, nuclear	60,000	8,580	1962	550
BELKNAP, oil-fired	85,000	7,930	1962	547

There must be weight differences in these ships other than those due to the power plant. Nevertheless, these and other data suggest a consistent trend and naval nuclear plants seem to weigh more than conventional plants, possibly in the neighborhood of the average value of 136 lb/hp. If true, this would be three times the specific weight of oil-fired naval plants without fuel, but still much less than the specific weights of merchant-nuclear plants.

From the last of these estimates, it appears that nuclear plants for naval ships are approaching "parity" in cruiser-size vessels, but that substantial reductions in the installed plant weight are required to match the performance needed in destroyers.

Now let us turn to another topic, the price-performance of nuclear propulsion. Some of the relevant data reported for civil construction are the following:

Ship	Total Cost ($ Million)	Reactor Cost ($ Million)	Reactor Cost Fraction	Specific Reactor Price ($/hp)
SAVANNAH	--	17.5	--	795
OTTO HAHN	14	7	0.5	700
MUTSU	15.4	7.4	0.48	740

These costs are much in excess of the $30 to $60/hp specific prices that characterize common diesel or gas-turbine engines. One reason is that the reactor "prices" suggested here include the extra fuel supply for a considerable period of time. The following core-life data are representative:

Ship	Full-Power Core Life (Years)
SAVANNAH	2.7
OTTO HAHN	1.37
LENIN	1.5
MUTSU	1.0

Each year of full-power core life is a credit against the comparable fuel cost of conventional plants. At 20¢ per gallon for fuel, each year of full plant power is readily computed to be worth \$175/hp. If the nuclear plant costs \$700/hp more to install, it would break even in cost with a conventional plant if it had a four-year core life, provided fuel is 20¢ a gallon. If fuel costs are 40¢ a gallon, however, the core life needed is only two years, and this has already been exceeded by the SAVANNAH. Thus, as fuel costs rise nuclear propulsion rapidly becomes more economically attractive.

These plants, however, are still very heavy and it is of interest to see what prospects there are of reaching lower specific weights.

G.3 RECENT DESIGNS

It has been pointed out that radiation shielding is the major source of weight in commercial vessels having nuclear power plants. Some discussion of this problem can explain how it occurs and how two different schemes may minimize it in the future.

Nuclear ships all use pressurized-water plants. The major radiation source is naturally the fuel material within the core. However, the water circulating through the reactor core is also highly activated. In absorbing a neutron, the oxygen portion of water emits a proton to become an unstable isotope of nitrogen. This decays, with a half-life of about 7 seconds, very frequently outside the reactor pressure vessel and primary shield and results in the emission of a 6- or 7-Mev gamma ray that is more intense than most of the gamma rays from the fission process. It is largely for this reason that the primary piping loops of pressurized-water plants need to have extensive shielding. Clearly, the shielded volume is much greater than the volume of the reactor pressure vessel itself.

This was recognized by Babcock and Wilcox in the design of OTTO HAHN, a successor to the SAVANNAH. Accordingly, the reactor pressure vessel was made sufficiently large that the steam generator heat-exchanger tubing could be contained within it. Then the Consolidated Nuclear Steam Generator (CNSG) could serve as a single, shielded steam-source analogous to a conventional boiler with an inherent fuel supply.

The validity of consolidation is confirmed by the "Unimod" series of designs from Combustion Engineering. These have powers in the range 10,000 to 60,000 hp. The 30,000-hp version weighs 430 tons for a specific reactor plant weight of 28.7 lb/hp.

Opposed to the above "pot" approach are the higher performance merchant-ship plants based upon piping. Two 1967 examples of these are the Westinghouse design based upon central-station concepts and the 22,000- to 120,000-hp NERO design from Reactor Centrum Nederland.

As a final example, in 1967 General Electric proposed a 630A Maritime Nuclear Steam Generator based on the aircraft nuclear propulsion development effort over the preceding decade. This scheme, interestingly, attacked the weight problem through smaller size, higher levels of heat transfer at high temperature, and a reactor coolant, helium, which would not become appreciably activated. It was conceded that the 630A plant is about the same size and heavier than the boiler it might conceivably replace. Notably, the condition of the steam supplied to the turbine throttle suggests a conventional, high-performance turbine plant. For comparison, this and the other designs mentioned are summarized in Table G-2.

TABLE G-2. CHARACTERISTICS OF VARIOUS REACTOR DESIGNS

Firm	Design	Horse-power	Type	Specific Weight, Reactor Plant (lb/hp)	Steam Supplied Pressure (psi)	Steam Supplied Temp. (^{o}F)	Superheat (^{o}F)	Full-Power Core Life (years)
B&W	CNSG	70,000	pot	39	700	553	50	3.5
CE	UNIMOD	30,000	pot	26.7	600	600	112	2.7
		60,000	pot	20.0	600	600	112	--
Westinghouse		75,000	pipe	43.6	620	490	0	3.4
Dutch-NERO	NERO	22,000	pipe	96.0	582	545	62	3.0
GE	630A	27,300	pot	34.0	1535	1005	405	1.98
		63,000	pot	12.5				
		126,000	pot	6.3				

A best appraisal of the first four of these came from the Euratom-funded study by Reactor Centrum Nederland and the Rotterdam Dockyard Company who (in 1969) compared the different types of pressurized water plants which might suit a 120,000-hp, 30-knot container ship. In concise form, their conclusions were:

1. Both types of nuclear plant increase ship weight by 2400 tons (40 lb/hp) due to heavier components and collision protection, and 3000 tons due to extra ballast for damage stability. This extra 5400 tons approximates the fuel for a conventional ship, or 90 lb/hp.
2. Nuclear plant requires more space, or a decrease of four containers, than a conventional plant.
3. There is no decisive advantage of one (PWR) reactor type over the other:
   a. For the loop-type plant the reactor vessel is smaller, lighter (107 vs. 275 tons), and easier to build. Also, steam generators require less than half the heat transfer area required for the integral type. However, the loop-type plant requires more space for the piping.
   b. The integral plant contains 50 percent more primary coolant so that a larger containment vessel or a higher pressure containment vessel is needed.
   c. For the integral plant, circulating pumps at the top of the pressure vessel tend to raise the center of gravity

undesirably and self-pressurization (through a steam bubble) cannot be used due to inadequate net positive suction heat at the pumps.

d. Integral plants will have marginally better performance since steam pressure is more nearly maintained at the turbine throttle during load variations.

e. Integral plants may have lower core temperatures during loss-of-coolant-flow accidents due to the inherent natural circulation within the reactor vessel.

Returning to Table G-2, one must reflect on this very impressive listing of design performance originating almost solely from commercial-economic motivation. One could add to the above conclusions the following:

1. The GE 630A, the sole design based on a gas-cooled reactor, would very likely require a machinery plant that is lighter than the pressurized water plants due to the higher temperature and pressure of steam used. Recent advances in high-temperature ceramics could enhance designs like the 630A.
2. The gas-cooled reactor concepts cannot be considered to have the same degree of reliability as pressurized-water plants simply because there is a smaller amount of experience with them at this time.
3. In military applications, one might expect that more expensive manufacture could yield levels of performance that are superior to those that are economical for the merchant marine. There may be ways to offset collison-protection structure by portions of the armor plating provided.
4. The data suggest that the specific weights of nuclear plants will be substantially less for plants of greater power. By choosing a nominal value for the turbines, auxiliaries, shafts, and propellors, such as 30 lb/hp, we might project total power plant specific weight for each of the commercial design concepts.

Design	HP	Specific Weight Total Power Plant (lb/hp)
CNSG	70,000	69
Unimod	30,000	59
	60,000	50
Westinghouse	75,000	73.6
NERO	22,000	126
630A	27,300	64
	63,000	42.5
	126,000	36.3

5. Except for uncertainties such as redundancy, tolerable levels of shock loading, and maximum core life, it appears that representative commercial designs show performance that is comparable to or superior to that inferred for naval nuclear power plants. This may be discerned somewhat from a plot of the power plant specific weights versus installed power for these five concepts and for two representative warships, as shown in Fig. G.2.

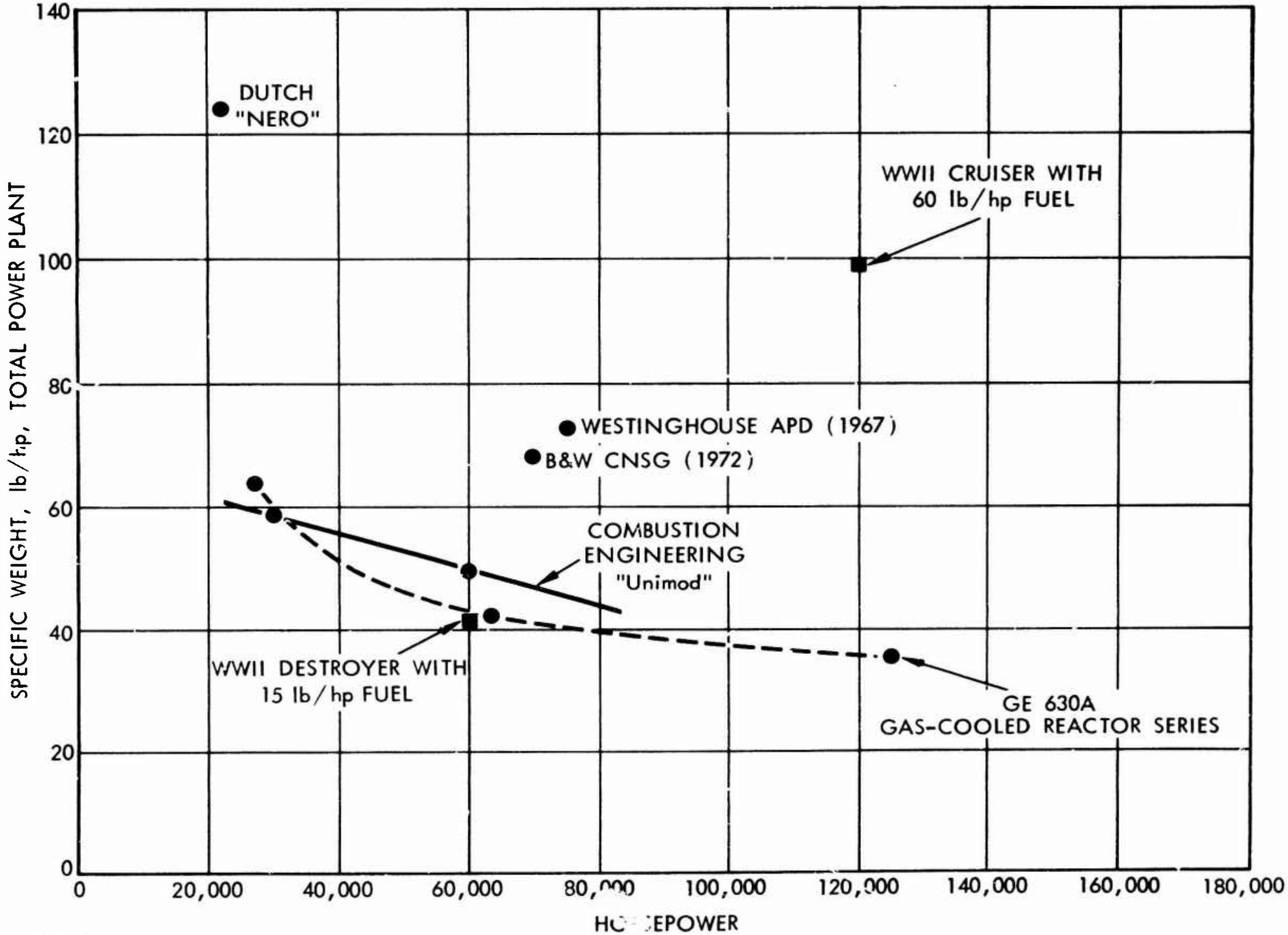

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FIGURE G-2. Concept--Specific Weight Versus Horsepower, Merchant-Type Marine Nuclear Power Plants